

# Present and future of LLP searches at LHCb

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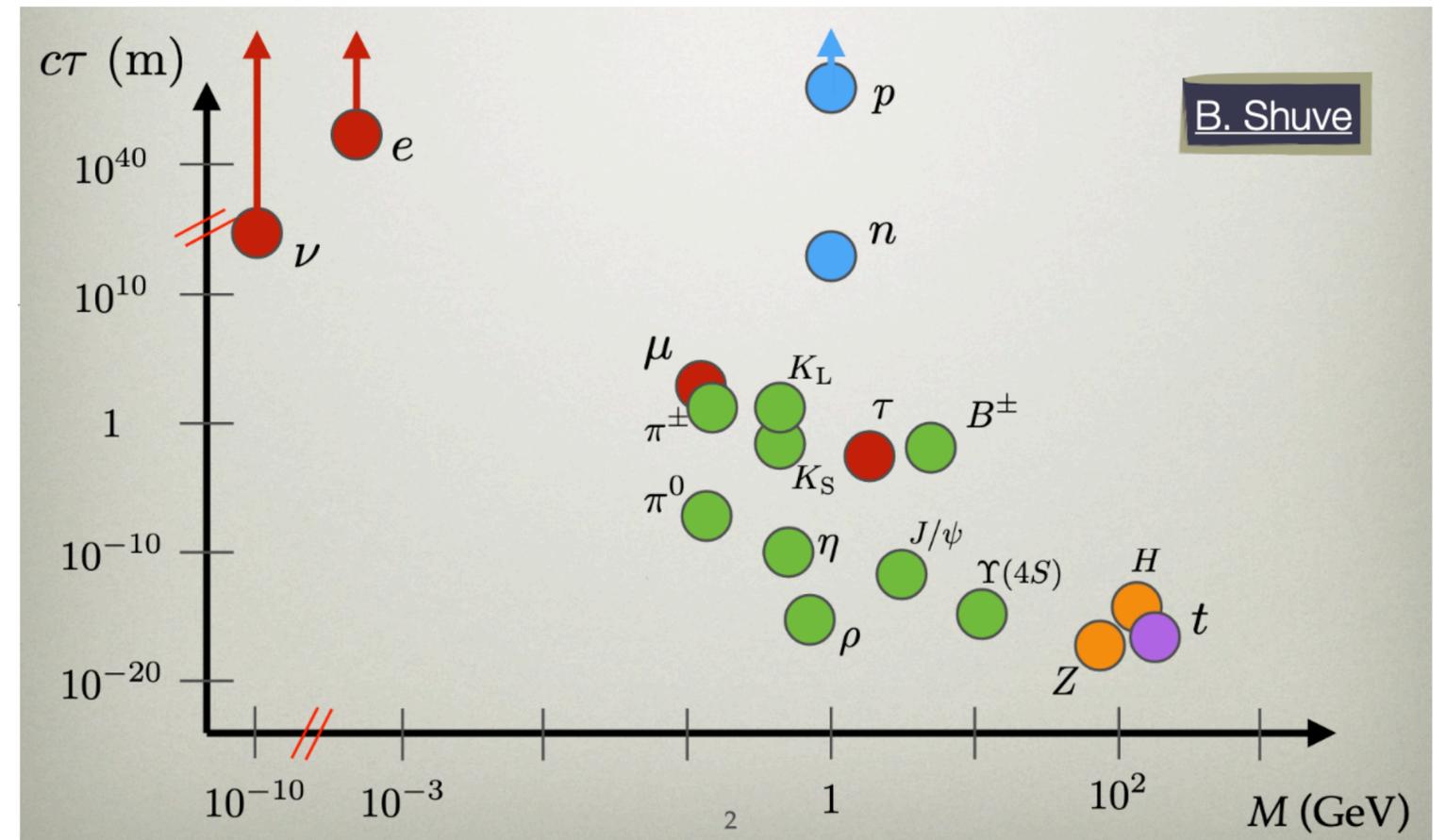
# Introduction

- In this talk I will give an overview of long-lived particle (LLP) searches in LHCb
- I will give a brief experimental background on the state of LLP searches in LHCb
- I will explain the recent advancements in triggering on Standard Model long-lived particles (strange hadrons) in LHCb
- Then we can look at the expected effect of applying these techniques to BSM LLP searches

# Long-lived particles

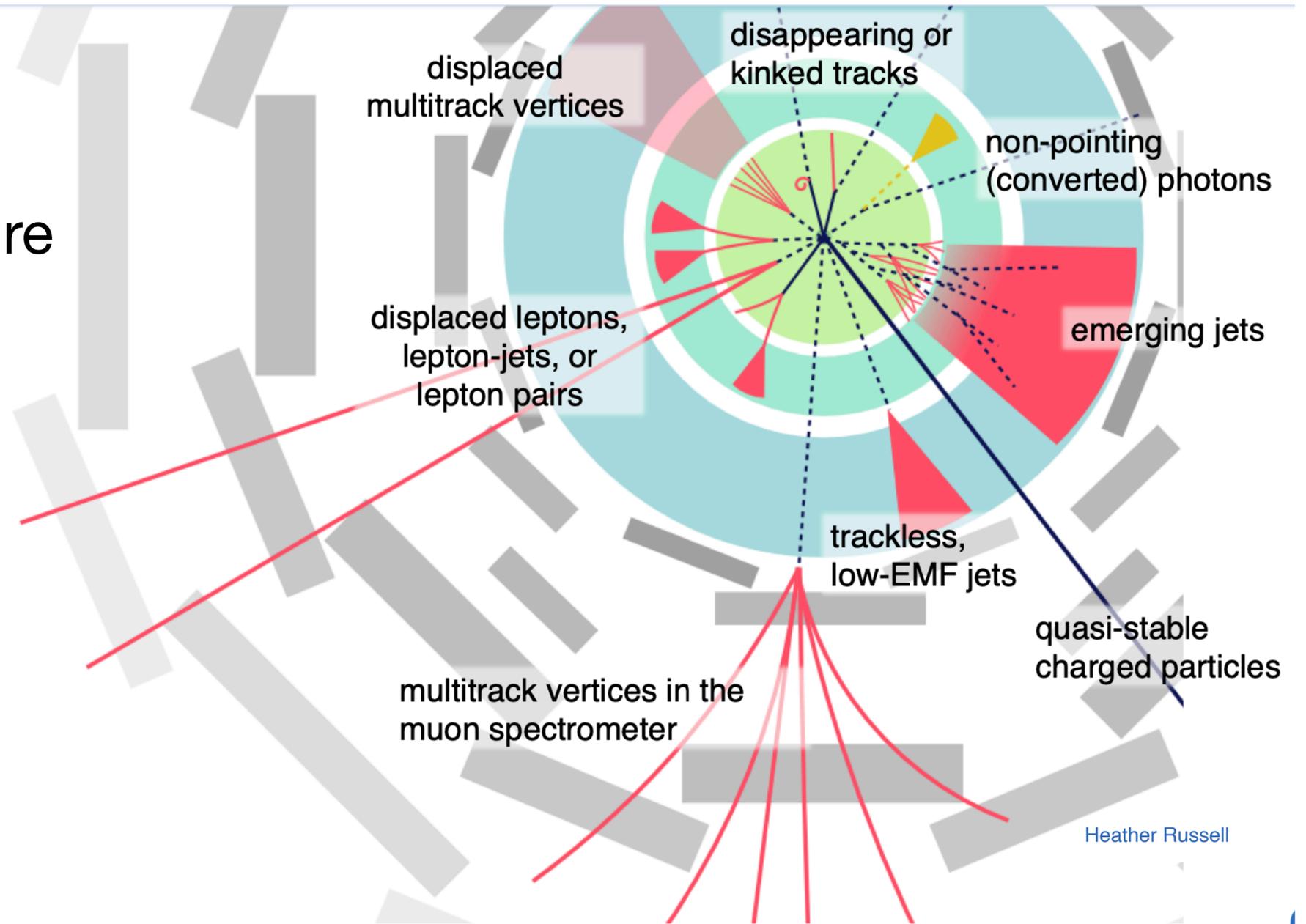
# Long lived particles

- What is a long-lived particle?
  - From an experimental point of view, they are particles that travel a reconstructible distance from the interaction point before decaying, also including (quasi-)stable particles
- More subjectively used to refer to particles that travel a (substantially) greater distance than the particles you usually study
  - Nowadays mainly used to refer to BSM LLPs
- Many BSM theories predict LLPs



# Types of signatures

- LLP searches tend to be signature driven rather than theory driven
- Many signatures are possible depending on kinematics, final state particles etc
- LLPs require dedicated tools to identify, since almost all LHC physics focuses on decays very close to interaction point
- Many new dedicated experiments



# Previous measurements

# Current status

## ATLAS

### ATLAS Long-lived Particle Searches\* - 95% CL Exclusion

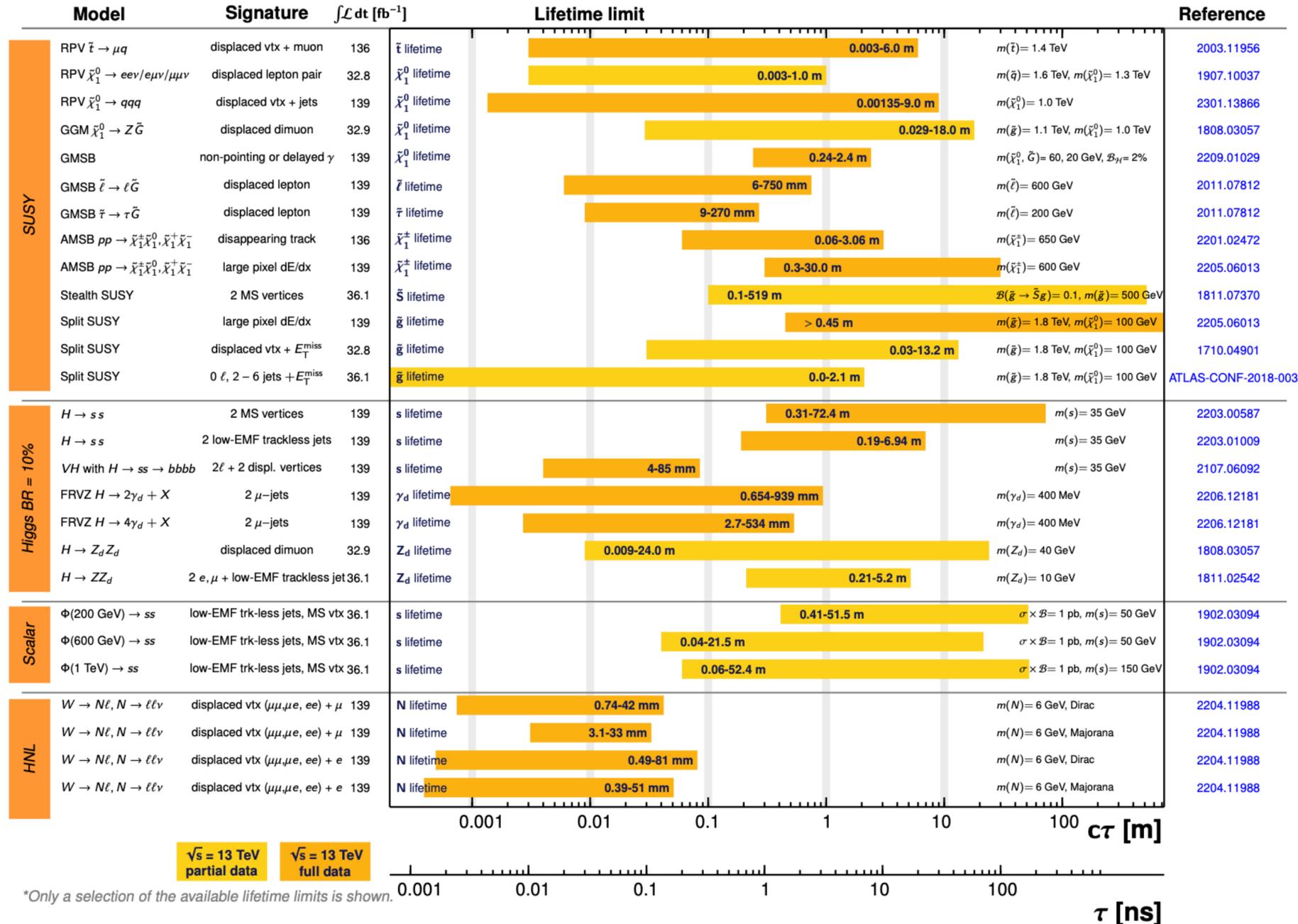
Status: March 2023

ATL-PHYS-PUB-2023-008

ATLAS Preliminary

$\int \mathcal{L} dt = (32.8 - 139) \text{ fb}^{-1}$

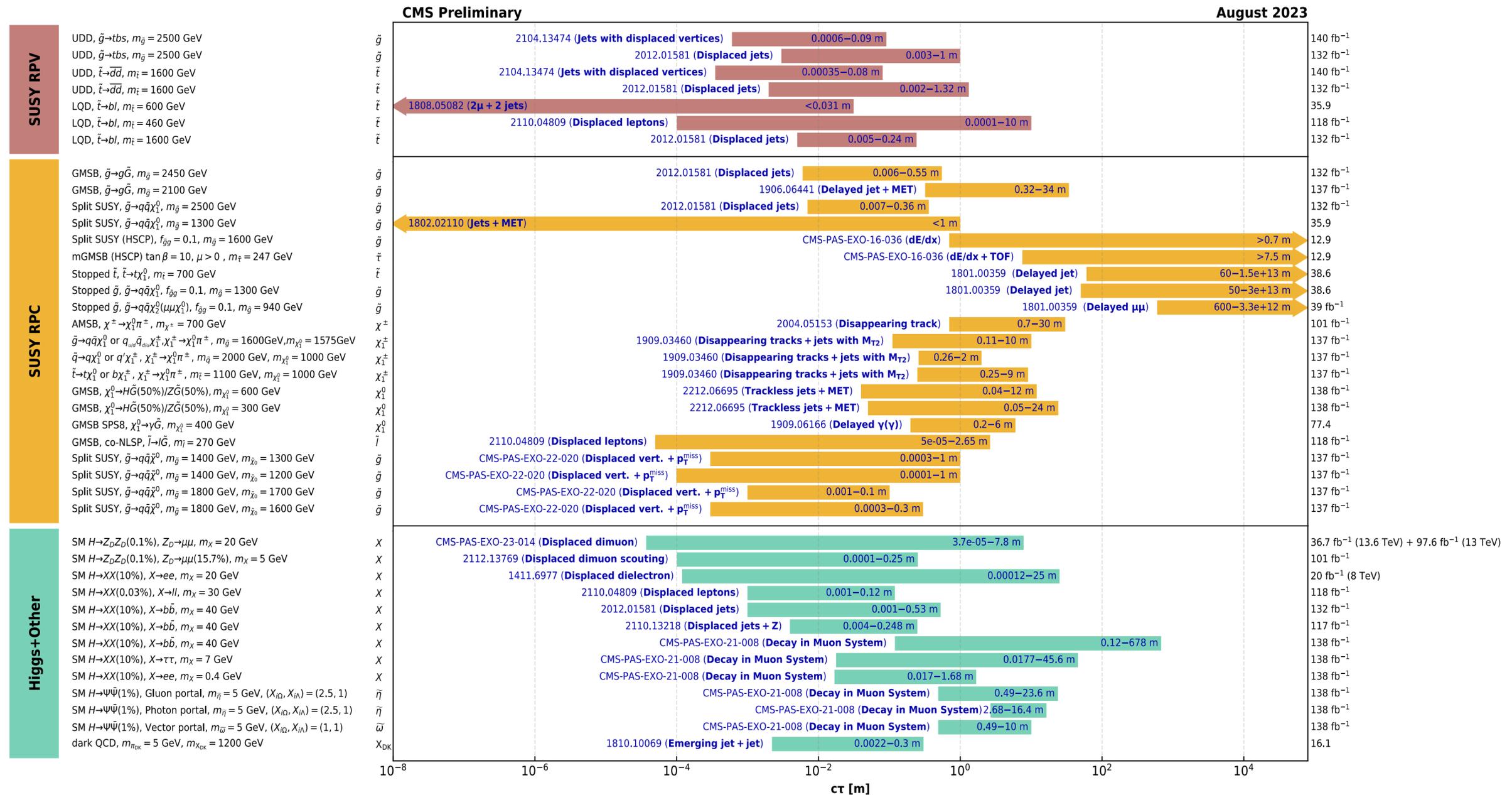
$\sqrt{s} = 13 \text{ TeV}$



# Current status

## CMS

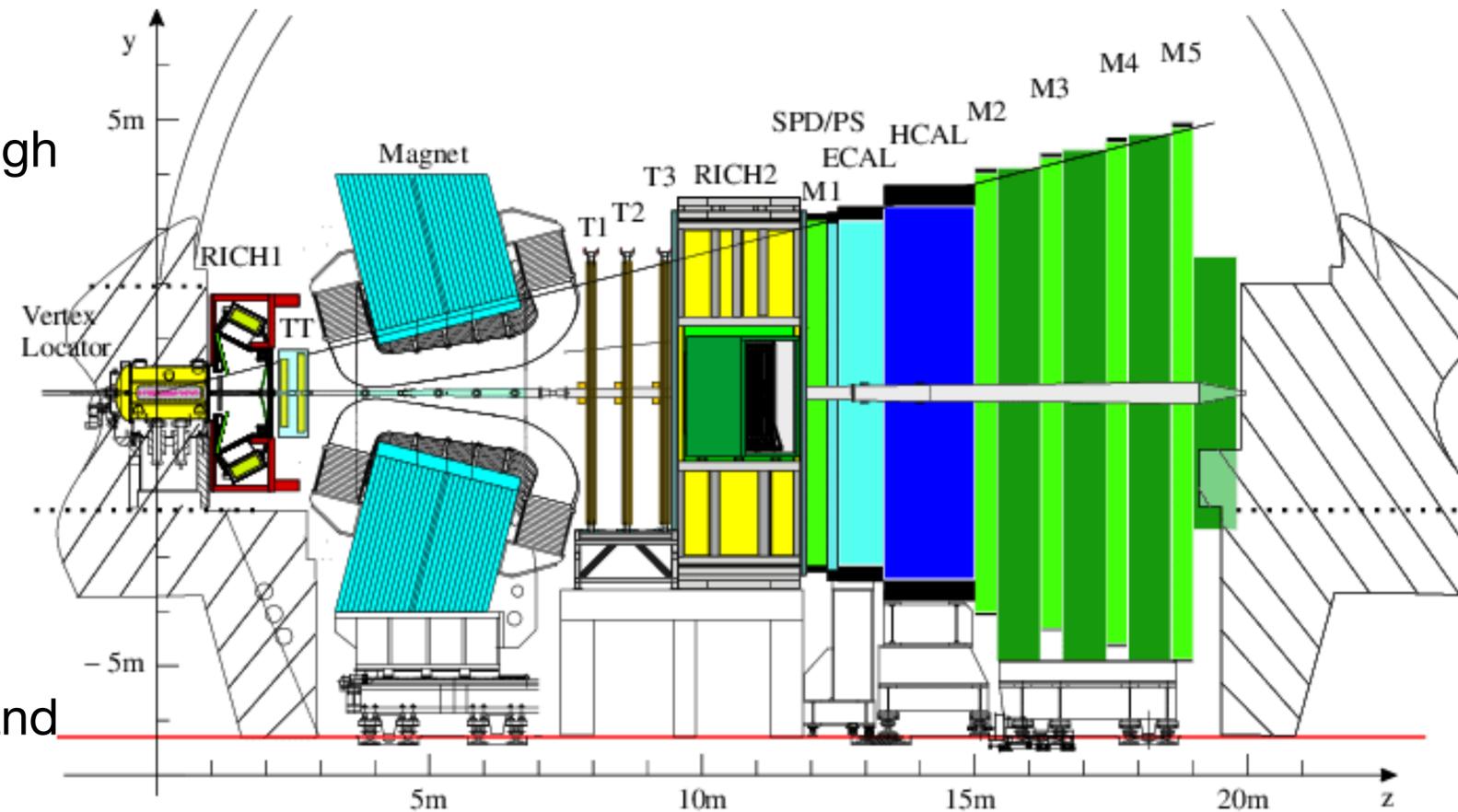
### Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle. [link to source](#)

# LHCb detector prior to Run 3

- General-purpose single-arm forward spectrometer
- Pseudorapidity range  $2 < \eta < 5$
- Optimised for study of particles containing b or c quarks, though physics programme has **expanded** beyond this
- Three tracking subdetectors:
  - VELO (vertex locator) located around the beamspot
  - TT (Tracking Turicensis) located before the dipole magnet
  - T1-T3 (tracking stations) located after the dipole magnet
- Also comprised of two RICH detectors for PID, ECAL, HCAL and muon stations
- Optimised for study of particles decaying close to interaction point
  - BSM LLPs could be hiding far from here
- Phase-I upgrade for Run-3



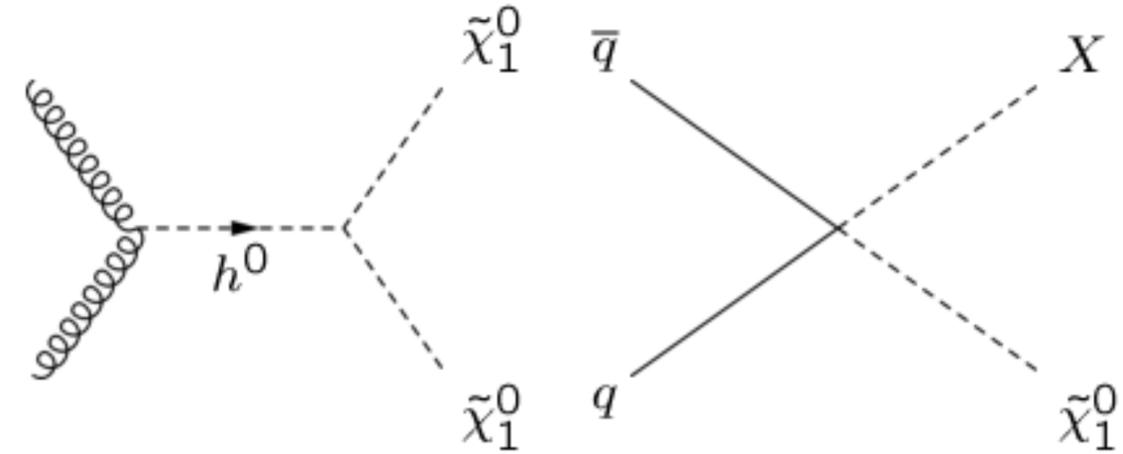
Source [Int.J.Mod.Phys.A 30 \(2015\) 07](#)

# Previous measurements in LHCb

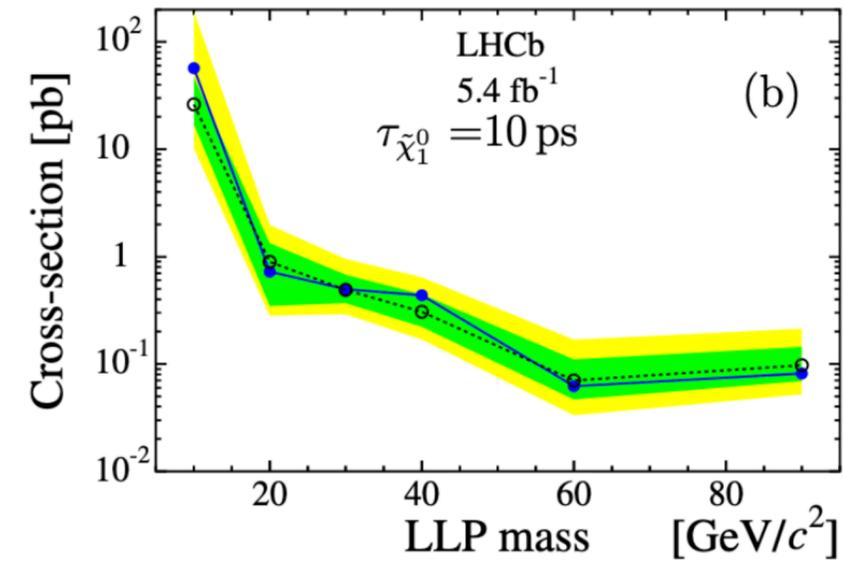
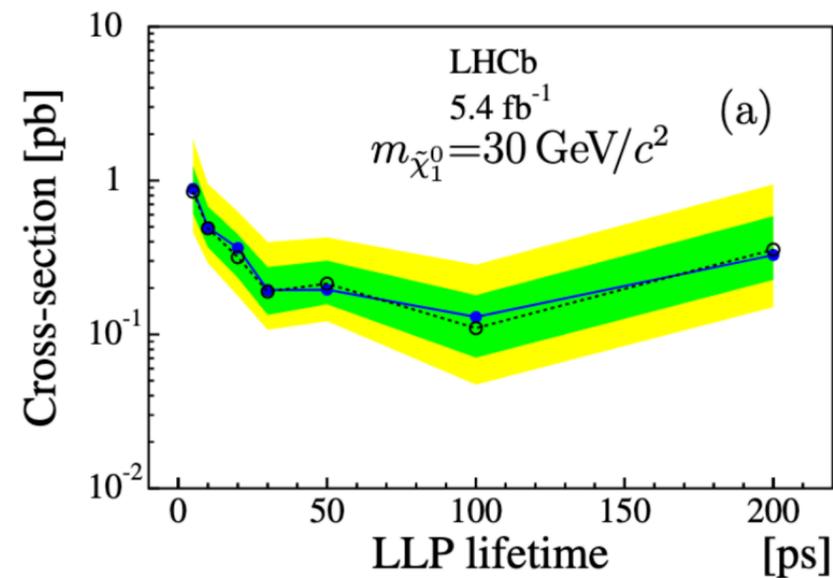
- Previous measurements in LHCb include search for massive long-lived particles decaying semileptonically, dark photons, searches for low-mass dimuon resonances, heavy neutral leptons (HNLs)
  - Measurements at  $\sqrt{s} = 7, 8$  and  $13$  TeV
- Measurements are looking for signatures in the VELO, up to  $\sim 1$  m from the interaction point
- LHCb most sensitive to LLPs produced in B hadron decays
- This limits the accessible lifetimes to  $\mathcal{O}(100)$  ps

# Massive LLPs decaying semileptonically

- Production: either in gluon fusion or non-resonant
- Lifetimes in the range [5,200] ps
- LLP signature is a displaced vertex made of charged particle tracks accompanied by an isolated  $\mu$  with high  $p_T$
- Lifetimes much higher than B meson ( $\sim 1$  ps) but still within VELO acceptance
- Un-binned extended maximum-likelihood fit to the distribution of the reconstructed LLP mass
- 95% CL upper limits are computed on  $\sigma(\text{LLPs}) \times B(\text{LLPs} \rightarrow \mu q \bar{q})$  for both production modes

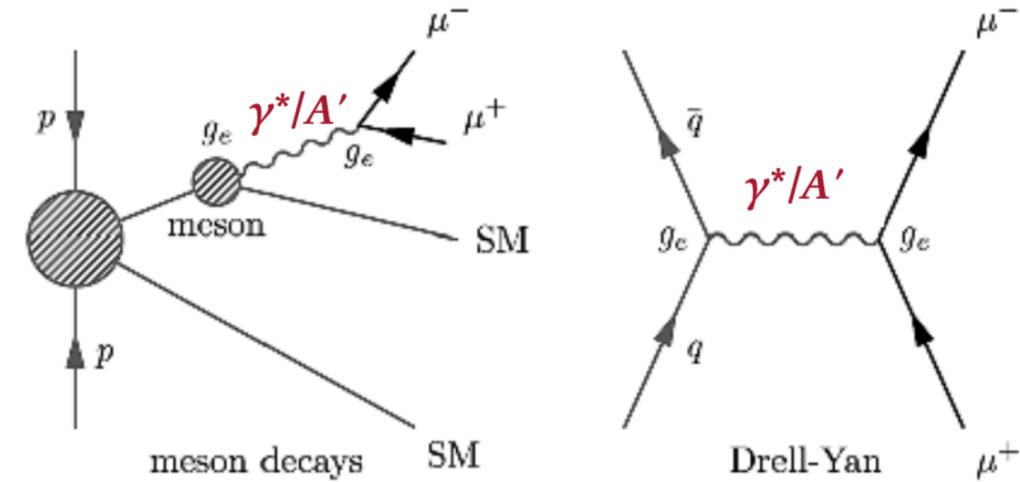


[arXiv:2110.07293]

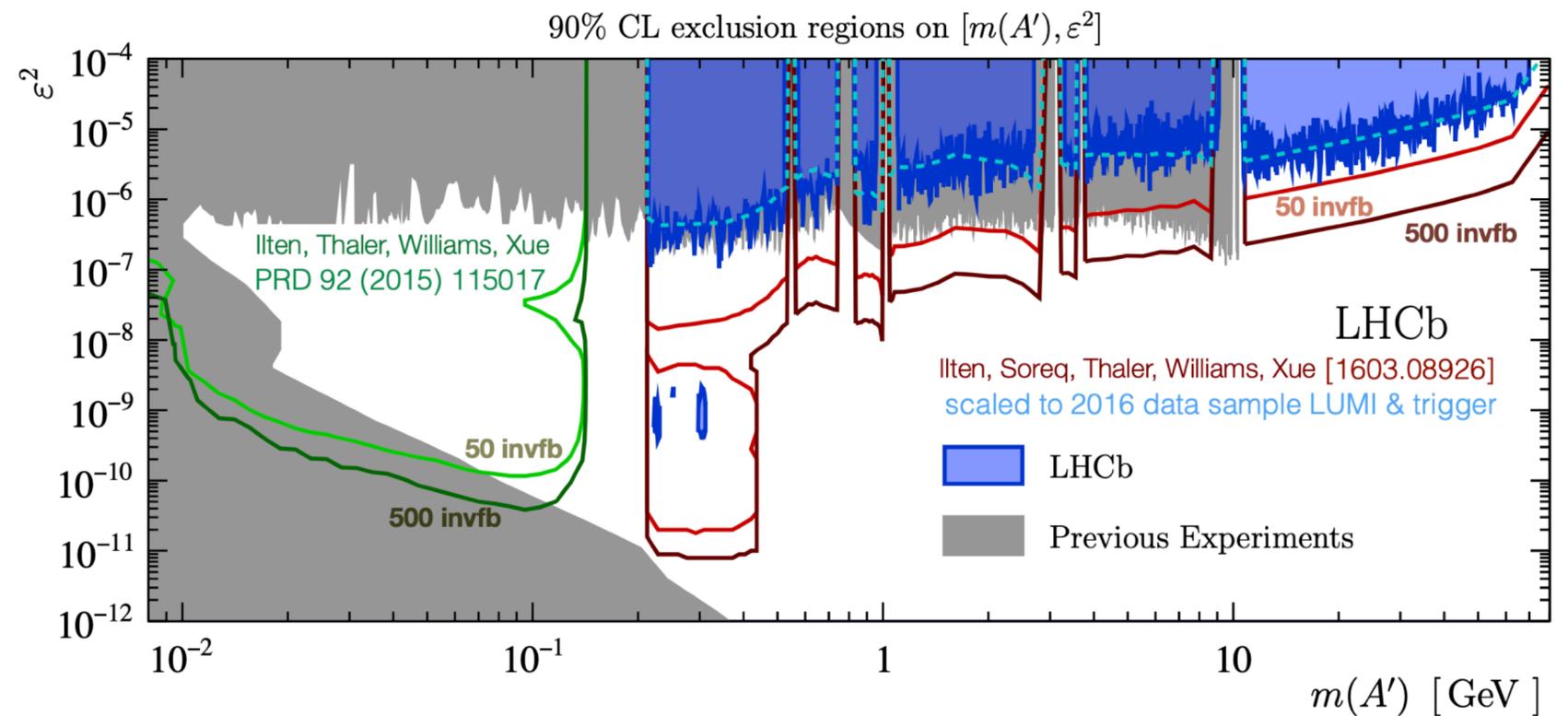


# Dark photons

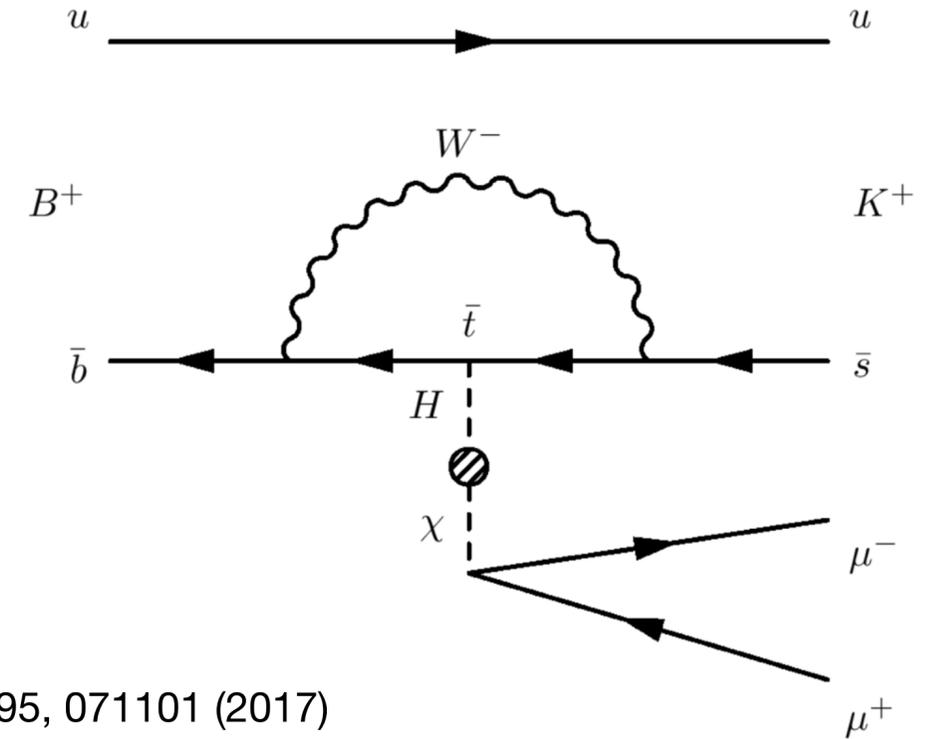
- Searches for prompt and displaced dark photons decaying into pair of muons
- $A'$  is long-lived only if the mixing factor is really small
- Fully data-driven analysis
- First limits on masses above 10 GeV & competitive limits below 0.5 GeV



$$n_{\text{ex}}^{A'}[m(A'), \epsilon^2] = \epsilon^2 \left[ \frac{n_{\text{ob}}^{\gamma^*}[m(A')]}{2\Delta m} \right] \mathcal{F}[m(A')] \epsilon_{\gamma^*}^{A'}[m(A'), \tau(A')]$$

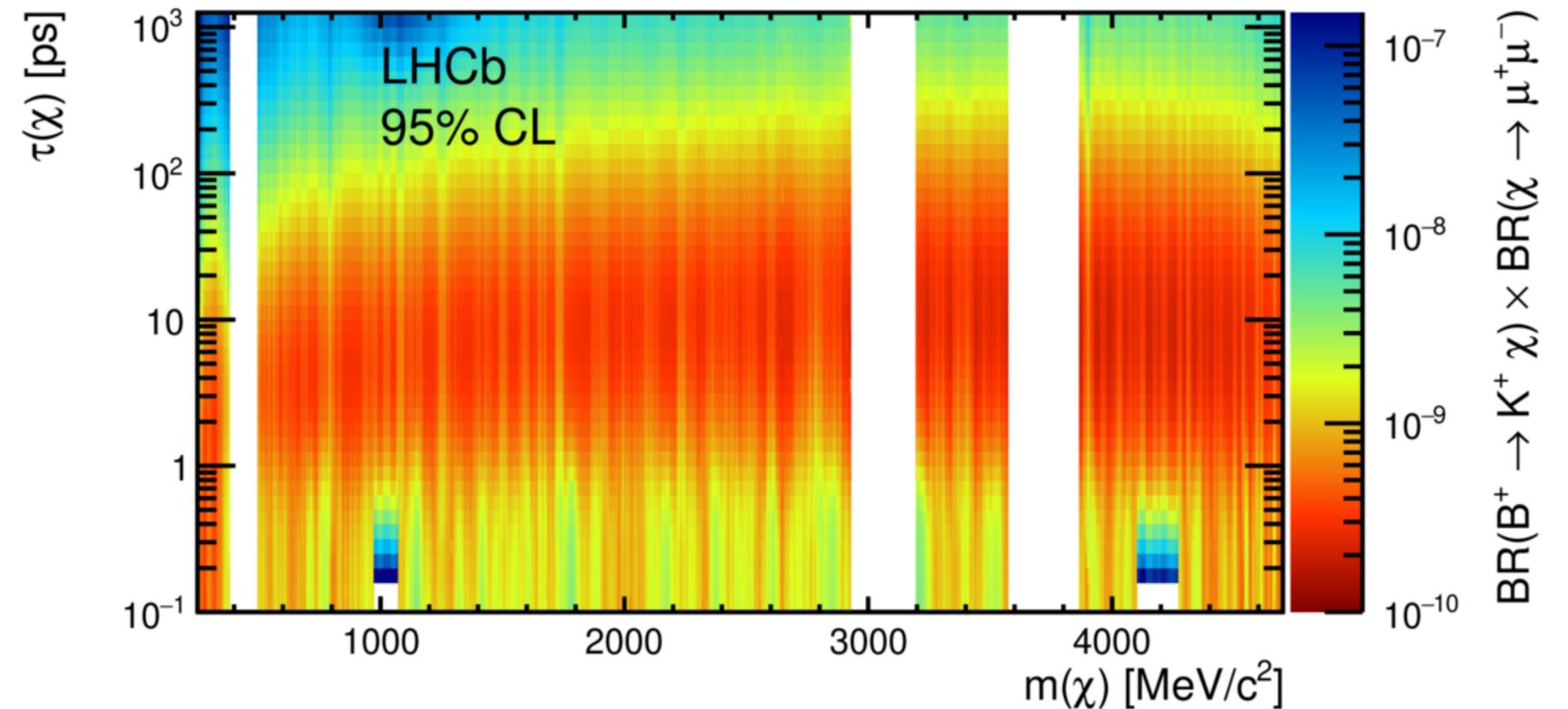


# Scalar boson $B \rightarrow K^+ \chi (\rightarrow \mu^+ \mu^-)$



Phys. Rev. D 95, 071101 (2017)

- Search for a scalar LLP decaying to a pair of muons
- Limits span over 3 orders of magnitude ( $10^{-10} \rightarrow 10^{-7}$ )
- Lifetimes span 0.1ps  $\rightarrow$  1 ns
- Using decays in the VELO

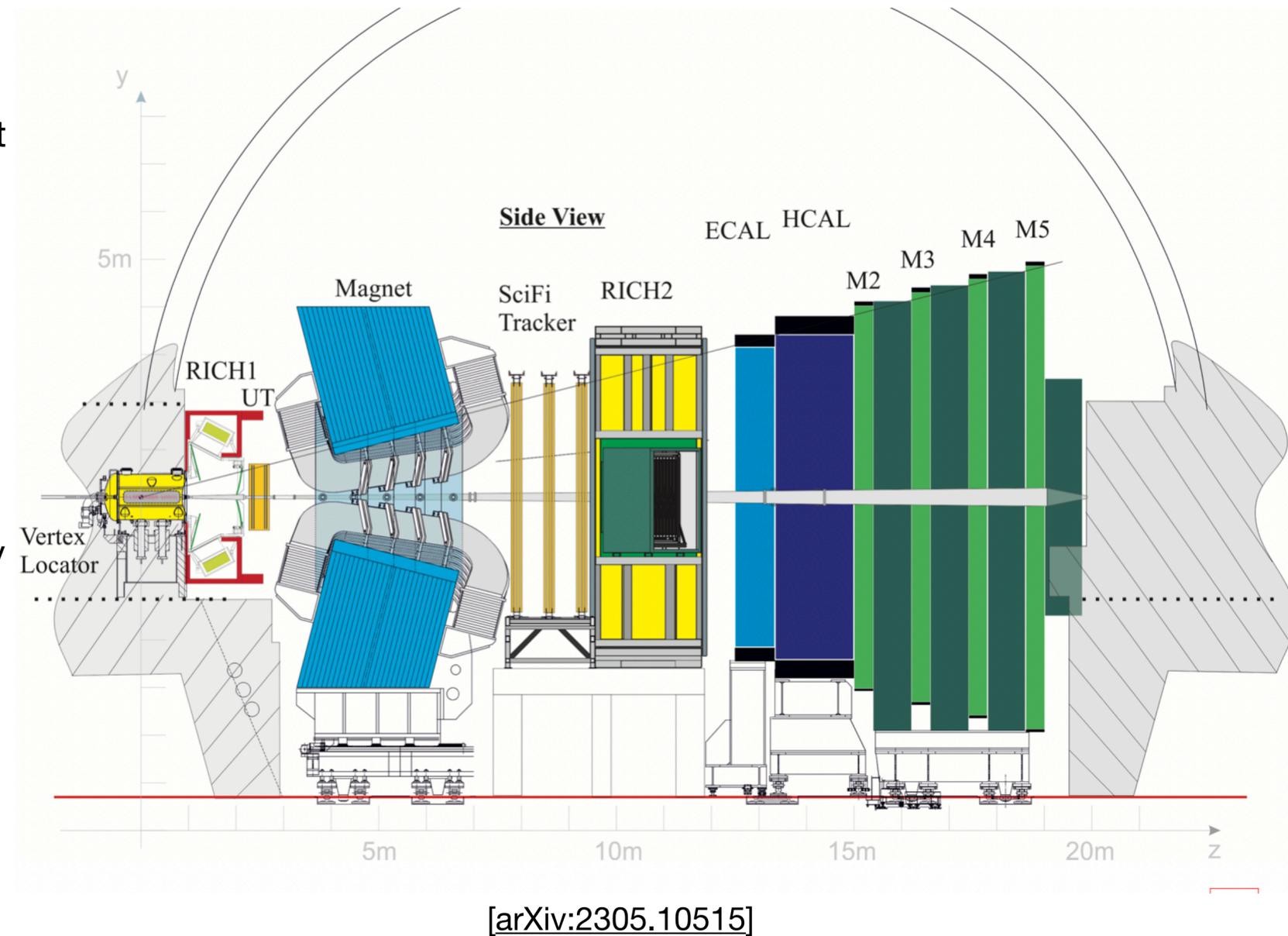


BR upper limit (95% C.L.)  
Phys. Rev. D95 (2017) 071101

# Advancements in LLP triggering

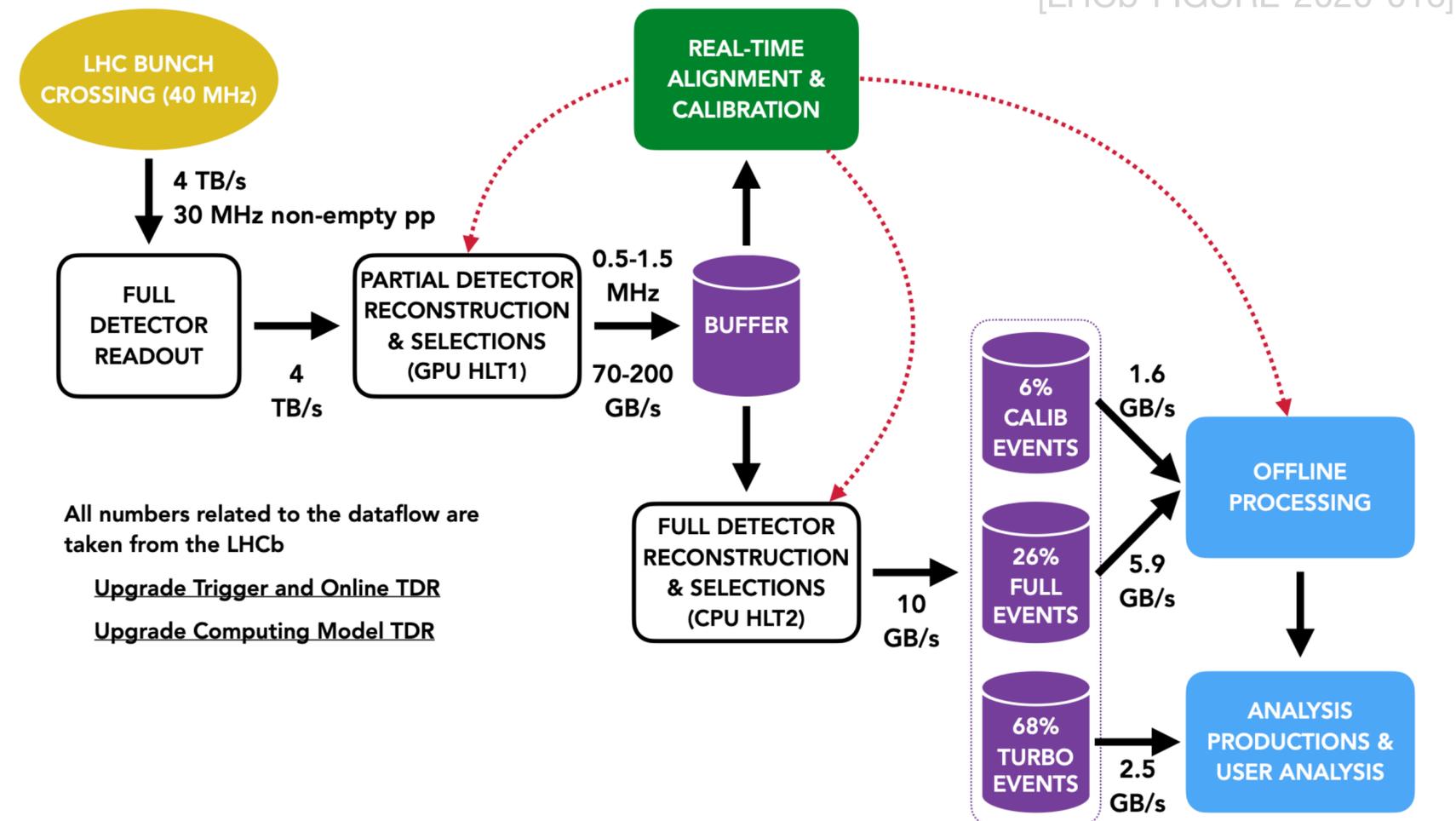
# LHCb Upgrade I

- Forward arm spectrometer,  $2 < \eta < 5$
- Particle tracking system is comprised of:
  - Silicon pixel vertex locator (VELO) around the interaction point
  - Silicon-strip upstream tracker (UT) in front of the large-aperture dipole magnet
  - Three scintillating fibre tracker (SciFi Tracker) stations downstream of the magnet
- Particle identification (PID) is provided by:
  - Two ring imaging Cherenkov detectors (RICH1 and RICH2) located upstream and downstream of the magnet respectively
  - Electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL)
  - Four stations of muon chambers (M2-5)
- Optimised for study of particles decaying close to interaction point
  - BSM LLPs could be hiding far from here



# LHCb trigger

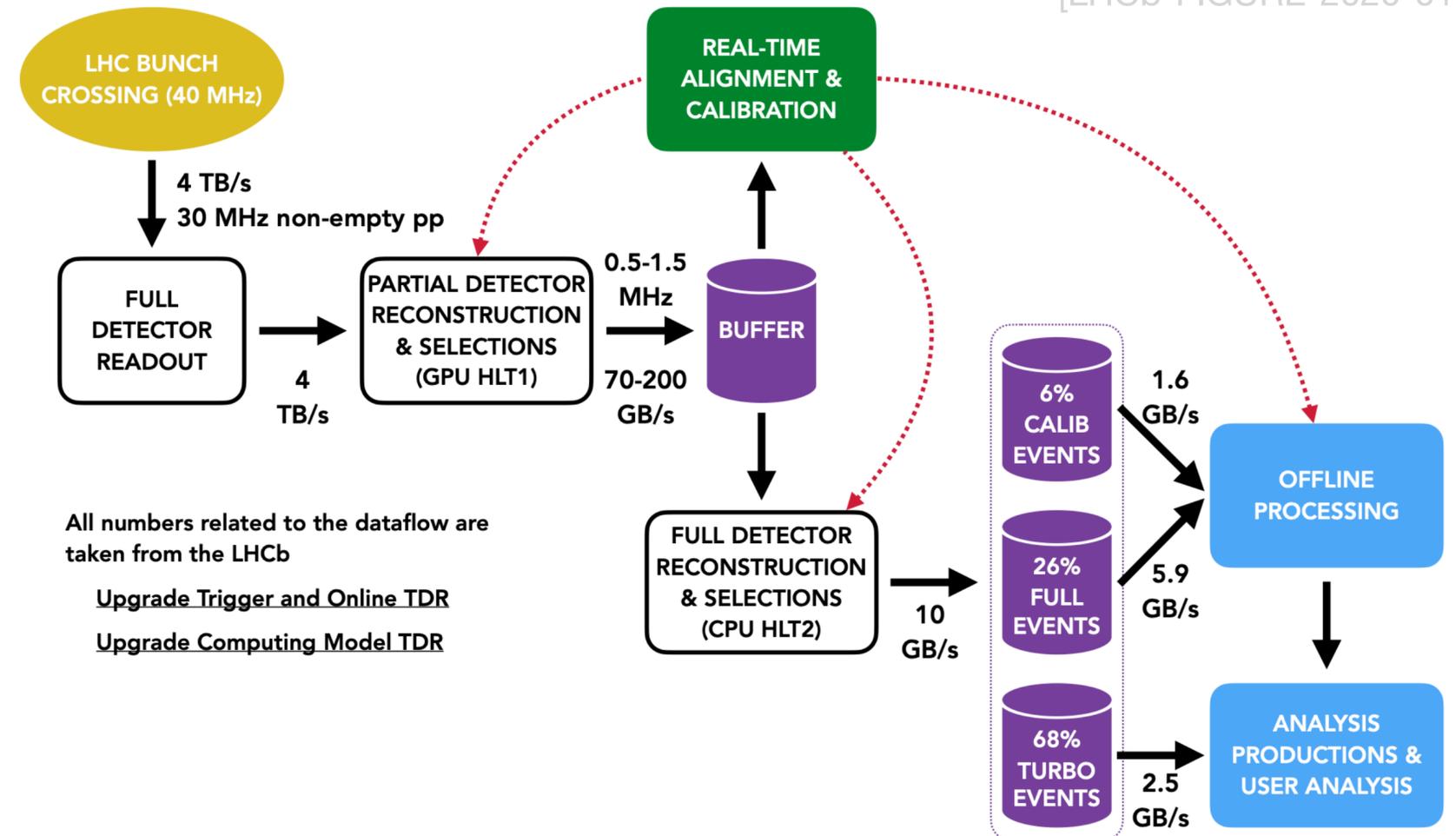
- For Run 3 LHCb has removed its hardware trigger
- Two-level software trigger: HLT1 (GPU) and HLT2 (CPU)
- Reduces data volume from 4 TB/s to 10 GB/s
- HLT1 provides a simplified reconstruction to reduce event rate by a factor 20
- HLT2 provides a full offline quality reconstruction to select signatures and reduce event rate by another factor 20
  - In general, only reconstructed objects belonging to the decay signature are persisted → Real Time Analysis (RTA) of data



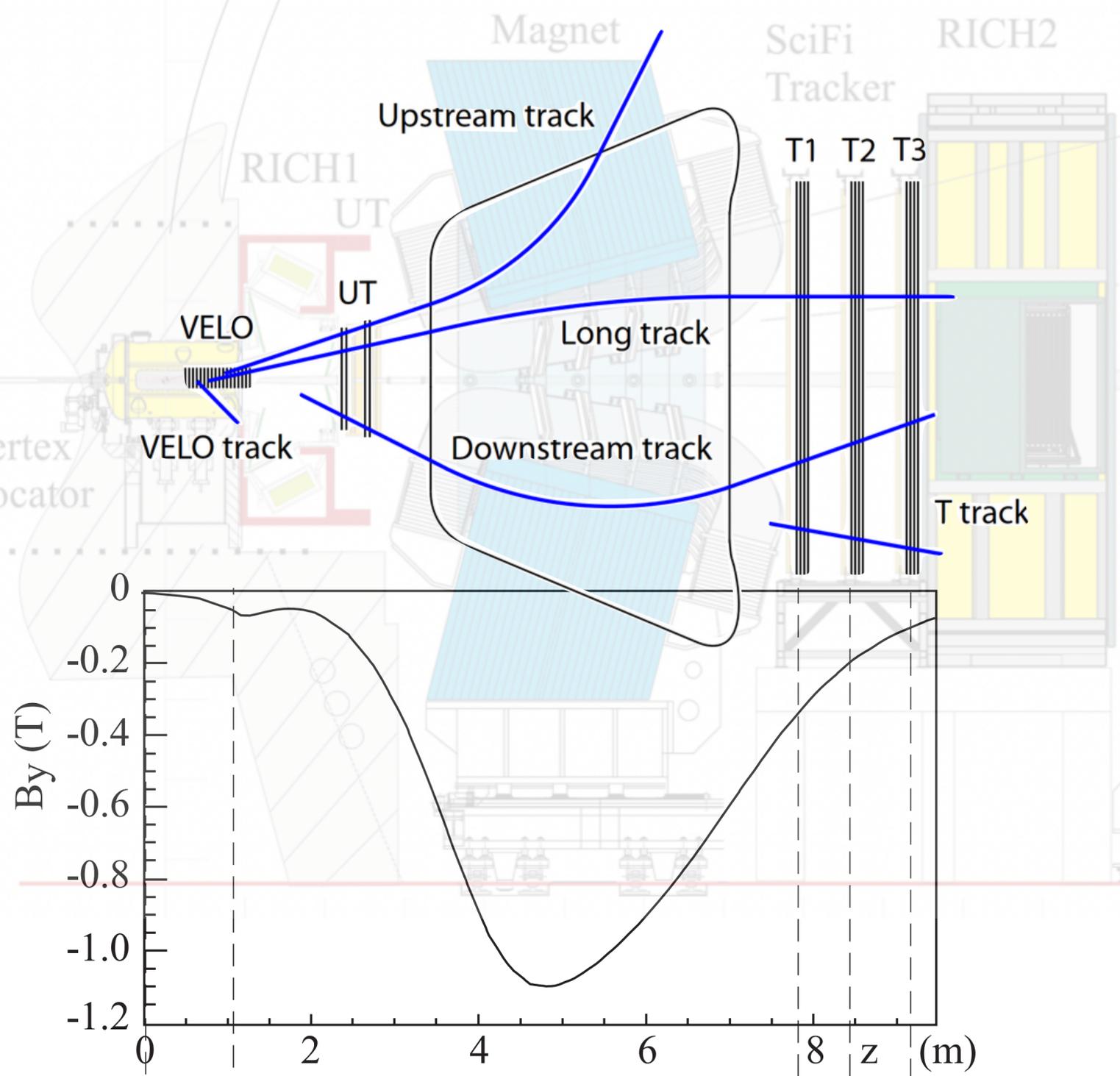
# LHCb trigger

- Algorithms and selections must meet strict throughput (events processed per unit time) and bandwidth (size of output data) requirements
- For decays in the magnet region there are three primary challenges which must be addressed:
  - Poor track momentum resolution
  - Extrapolation of trajectories through a strong, inhomogeneous magnetic field
  - Large track combinatorics

[LHCb-FIGURE-2020-016]



# Tracking in LHCb

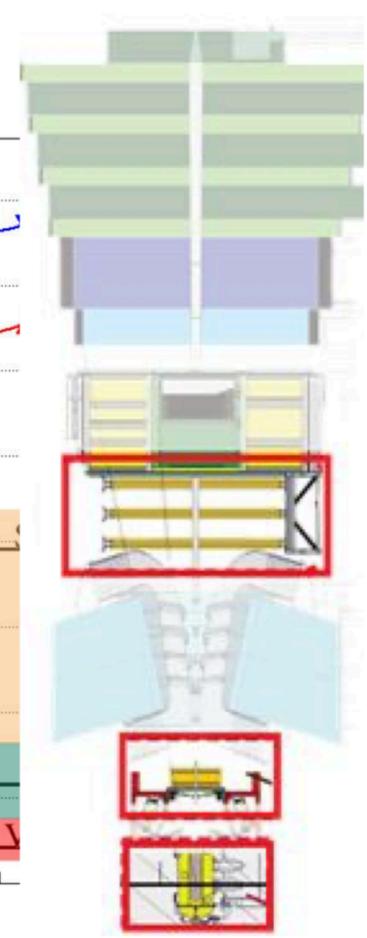
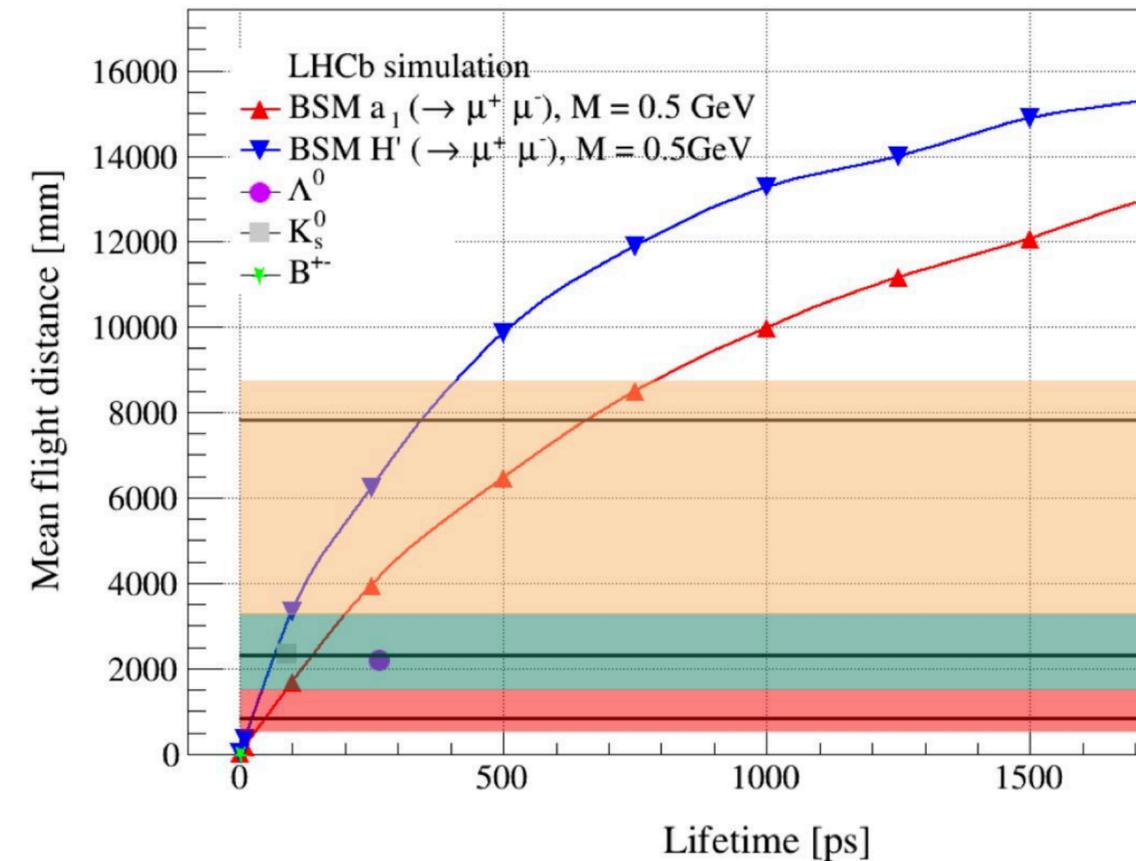


- Tracks reconstructed from segments in the different trackers, named according to where they have hits
- **Downstream tracks** and **T tracks** can be used to reconstruct long-lived particles such as strange hadrons, or undiscovered beyond the standard model (BSM) particles, that decay in the magnet region
- Downstream tracks used to reconstruct particles decaying 1-2 m from interaction point
- T tracks used to reconstruct decays up to around 7.5 m from interaction point
- The flexibility of the new trigger can be exploited to trigger on these signatures

# Downstream & T tracks in HLT1

## Why?

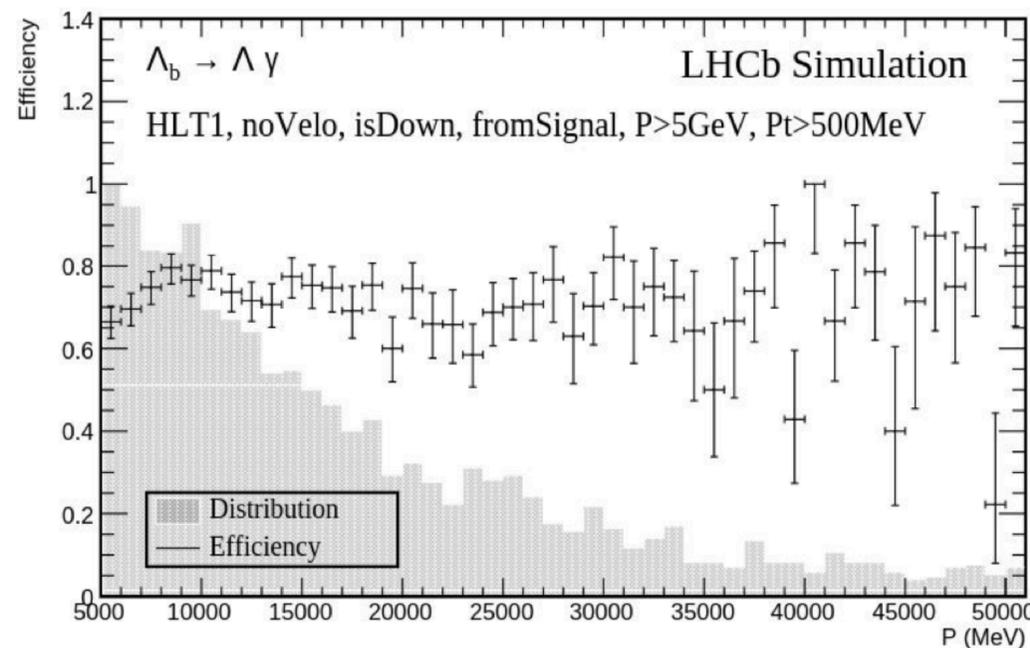
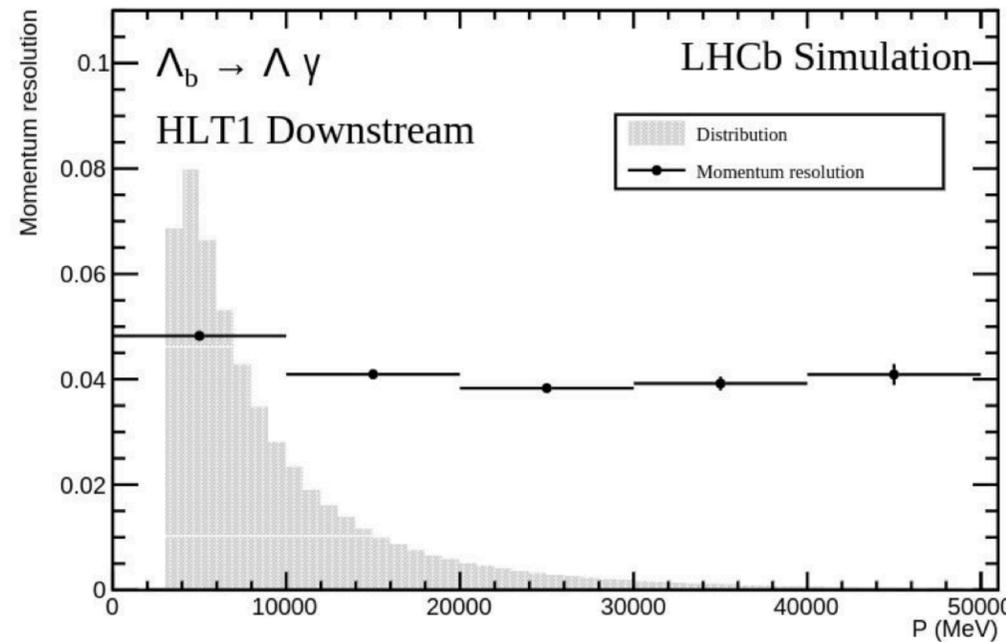
- Decays of particles with  $\tau > 100$  ps typically happen outside the VELO
- These particles decay to Downstream tracks and T tracks
- Weren't being selected by HLT1 before



L. Calefice *et al.* (2022). *Frontiers in Big Data*, [2022.1008737](https://doi.org/10.1008737)

# HLT1 Downstream

- Algorithm based on the extrapolation of SciFi seeds (or tracklets) to the UT detector, including the effect of the magnetic field in the x coordinate
- Search windows in the UT detector for hits that are compatible with tracks coming from the SciFi, and that are not used by other reconstruction algorithms, are considered
- In addition, fake tracks originating from spurious hits in the detector are suppressed by a neural network with a unique hidden layer
- The reconstruction efficiency for downstream tracks of the algorithm is about 70%, with ghost rates below 20%

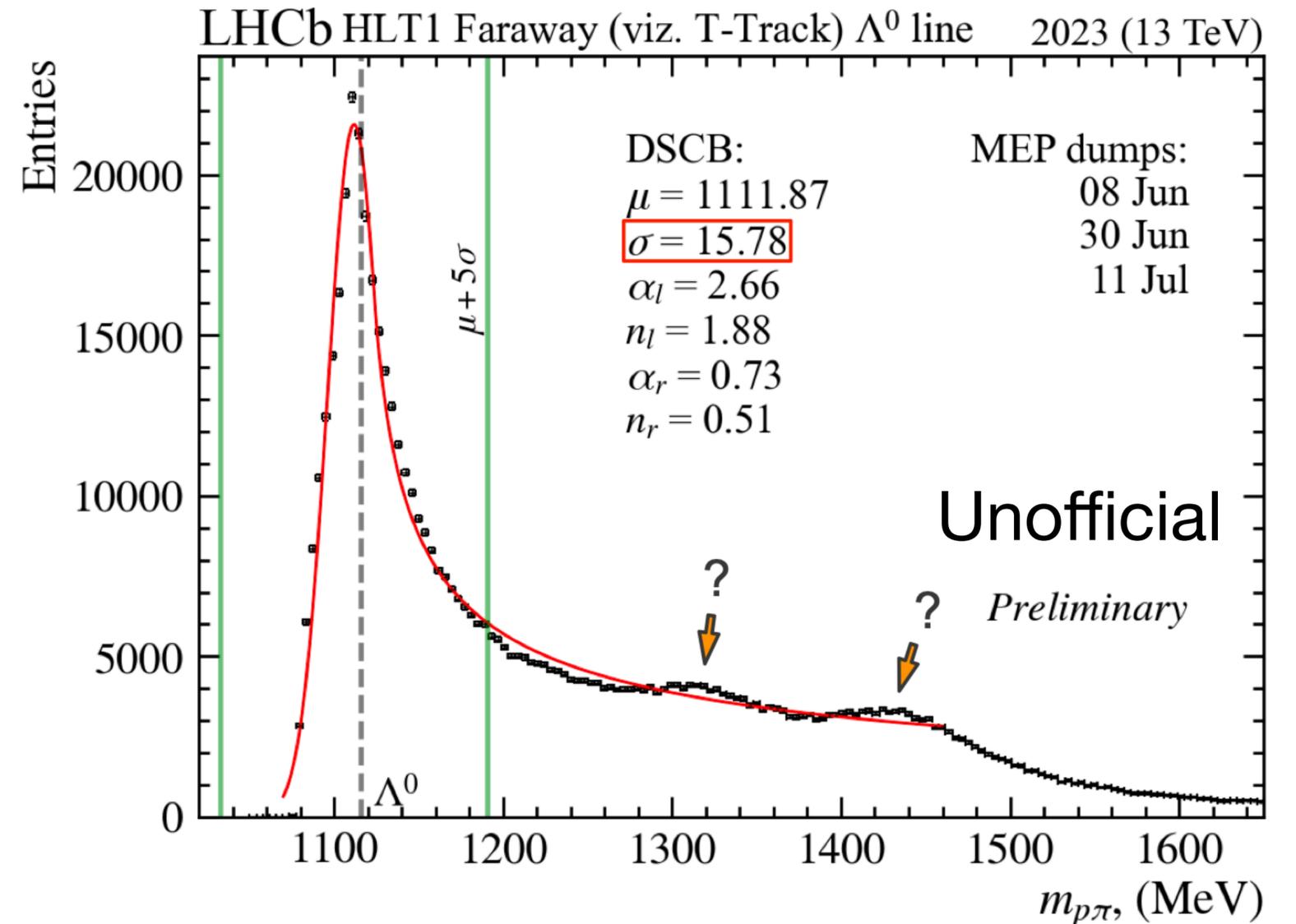


Channel	DD/LL proportion	Interest
<b>b-hadron decays</b>		
$\Lambda_b^0 \rightarrow \Lambda \gamma$	3.4	$\gamma$ polarization, BR
$\Xi_b^- \rightarrow \Xi^- \gamma$	25	$\gamma$ polarization, BR
$\Omega_b^- \rightarrow \Omega^- \gamma$	13	$\gamma$ polarization, BR
$B^+ \rightarrow K_S^0 K_S^0 \pi^+$	2.8	CPV, BR
$B^+ \rightarrow K_S^0 K_S^0 K^+$	2.7	CPV, BR
$B_s^0 \rightarrow K_S^0 K_S^0$	3.6	CPV, BR
<b>Charm physics</b>		
$\Lambda c^+ \rightarrow \Lambda K^+$	4.4	Polarization studies
$\Xi_c^- \rightarrow \Xi^- \pi^-$	8.4	Polarization studies
$D^0 \rightarrow K_S^0 K_S^0$	1.8	CPV
$J/\psi \rightarrow \Lambda \bar{\Lambda}$	4.8	Polarization studies, BR
<b>Strange physics</b>		
$K_S^0 \rightarrow \mu^+ \mu^-$	0.6	BR
$K_S^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$	0.8	BR
$K_S^0 \rightarrow \gamma \mu^+ \mu^-$	0.8	BR

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# HLT1 T tracks

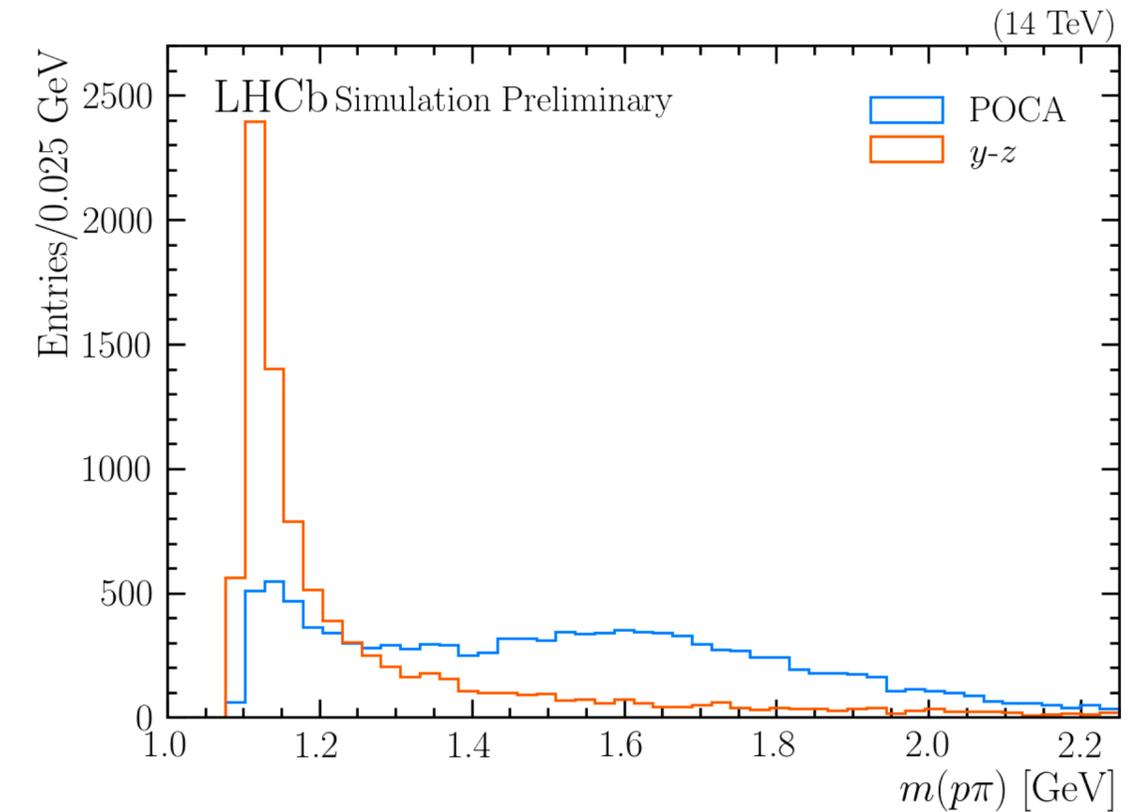
- Runs on remaining SciFi segments after Long and Downstream track matching
- Preselection of tracks from geometrical considerations
- Uses empirical extrapolation track model with parametrisation obtained from simulation to fit vertices in the magnet region
- Events selected using a neural network that uses quality and kinematical variables of daughter tracks and vertex as input
- Reduces throughput by around 1.5%
- WIP



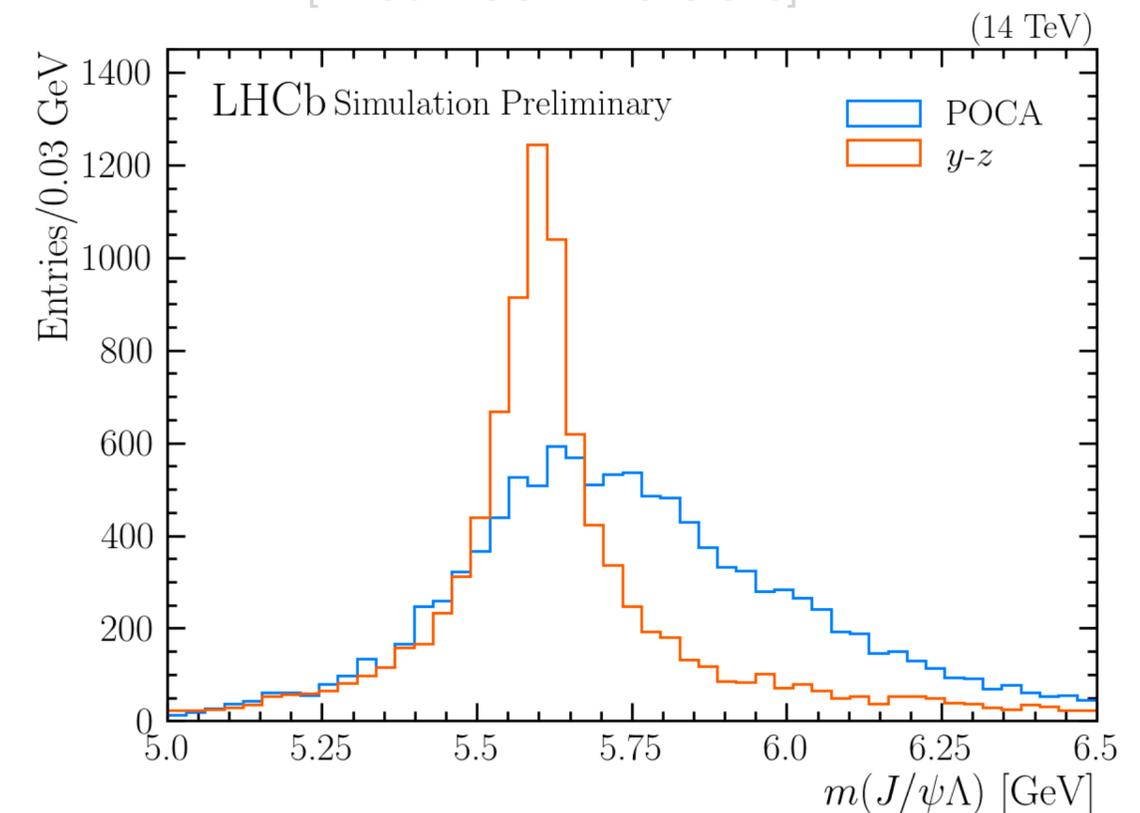
# Extremely displaced vertex finding and fitting in the magnet region

## HLT2 T tracks

- Narrow opening angle of  $\Lambda$  and  $K_S^0$  decay products used to reduce combinations in place of mass cuts
- Exploit linearity of tracks in  $y$ - $z$  plane to reject track pairs that do not cross in the magnet region
- For vertex fitting, use detailed 5th-order Runge-Kutta extrapolation in first iteration, polynomial interpolation after as compromise between timing and accuracy
- Mass resolution dramatically improved by using  $y$ - $z$  intersection instead of default point-of-closest approach (POCA) for vertex seed
- Further optimisations being investigated to simplify extrapolator to improve speed
- Mass resolution can be further improved by offline fitting



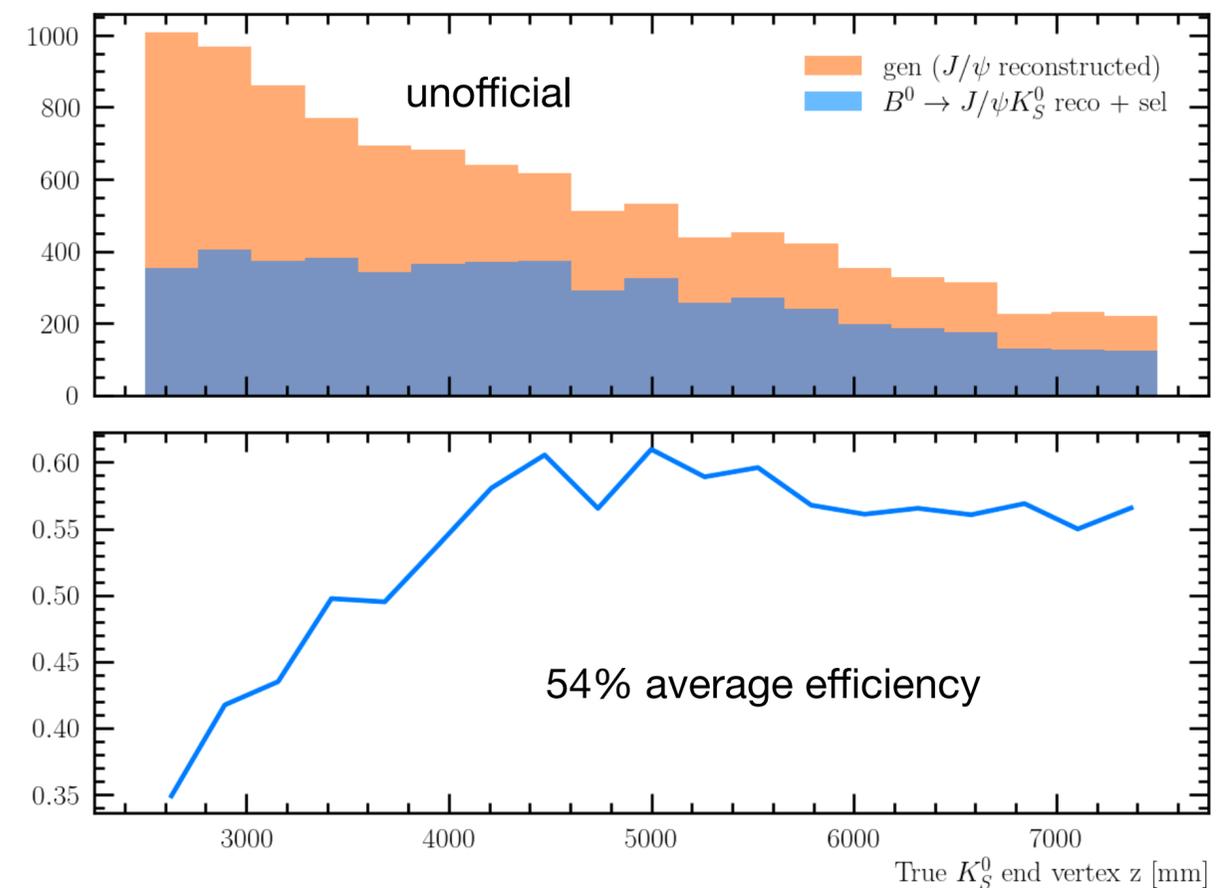
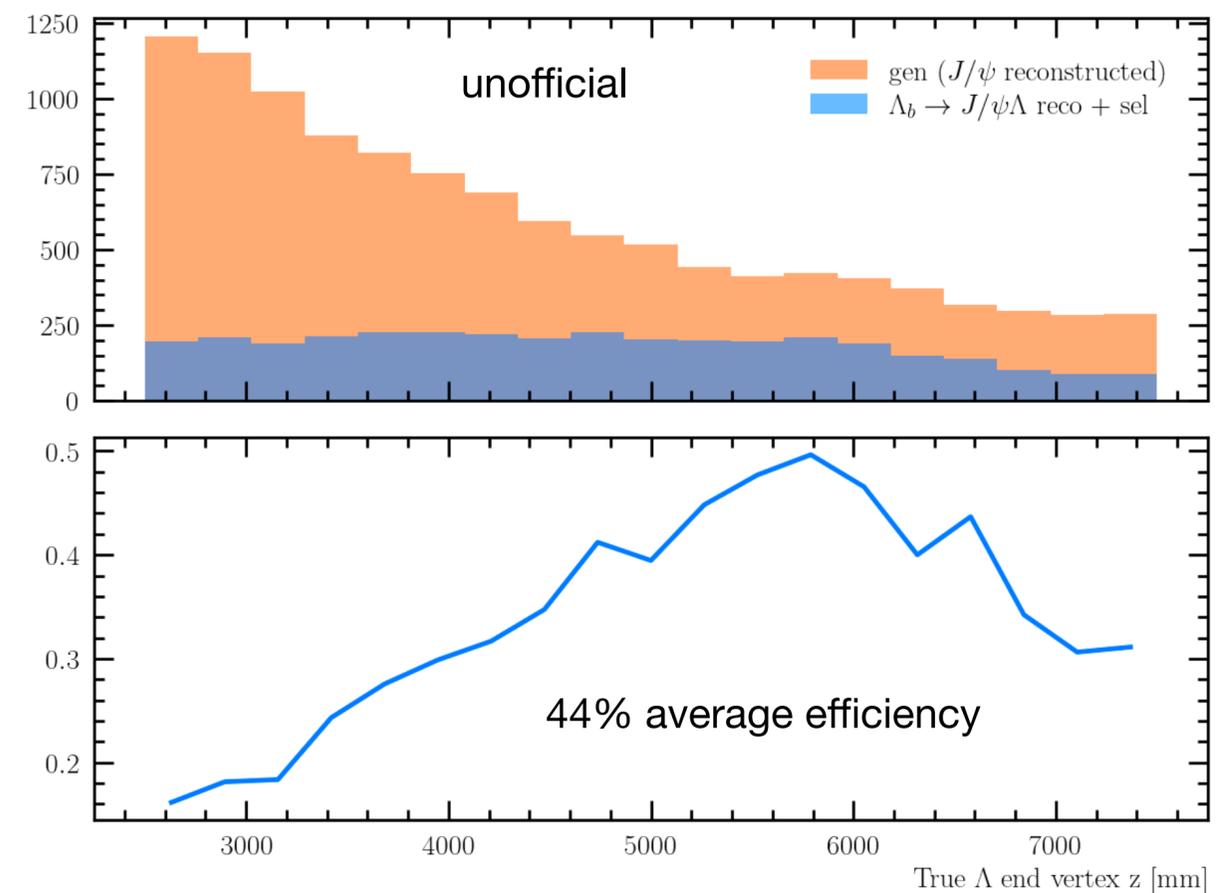
[LHCb-FIGURE-2023-026]



# Extremely displaced vertex finding and fitting in the magnet region

## HLT2 T tracks

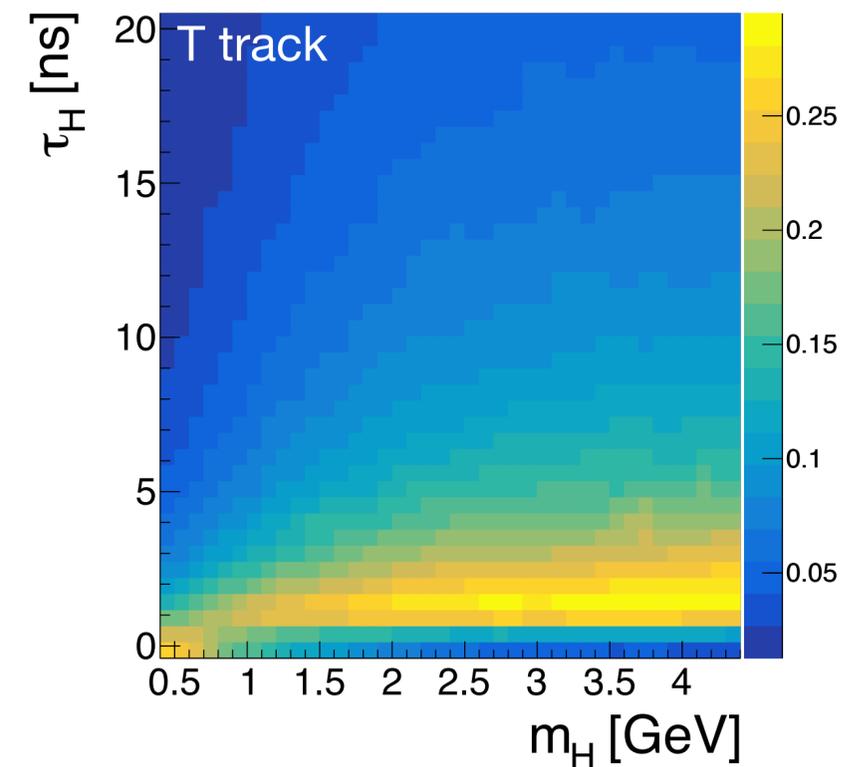
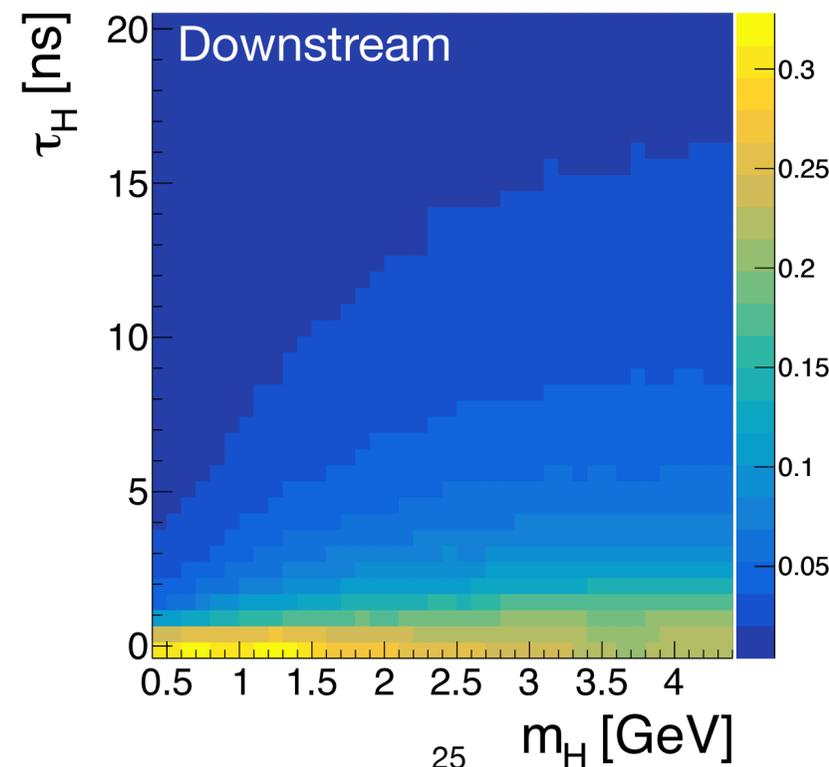
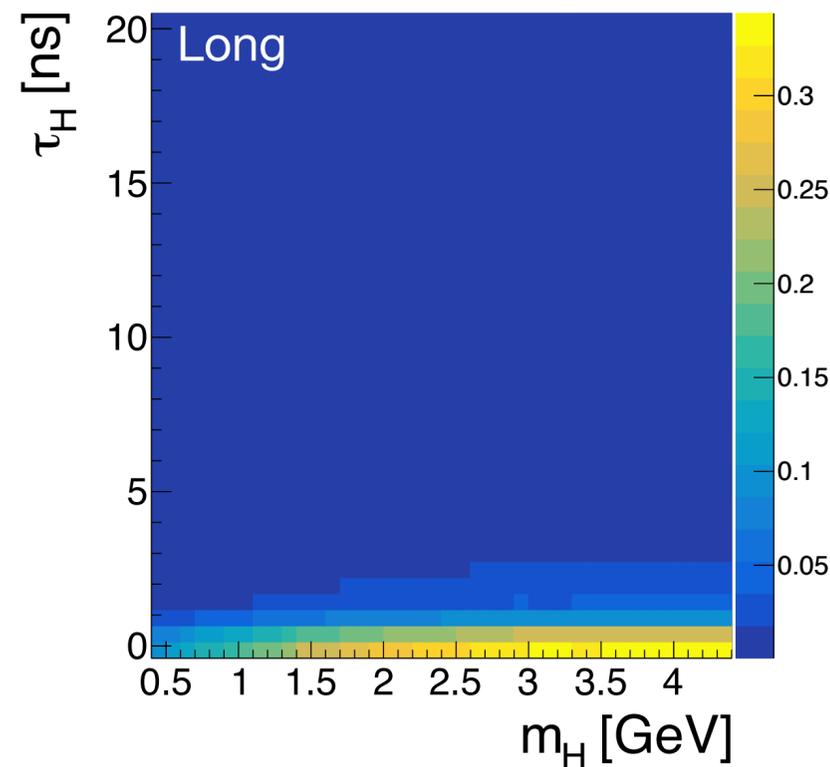
- Output rates  $\mathcal{O}(10 \text{ Hz})$  after vertexing T track and Long track combinations
- Currently deployed in trigger for  $\Lambda_b^0 \rightarrow J/\psi\Lambda$ ,  $B^0 \rightarrow J/\psi K_S^0$ ,  $J/\psi \rightarrow \Lambda\bar{\Lambda}$  decays
- Efficiencies shown after selections and vertexing wrt generated events where is  $J/\psi \rightarrow \mu\mu$  reconstructed
- To be updated for 2024 conditions



# LLP search prospects

# Prospects

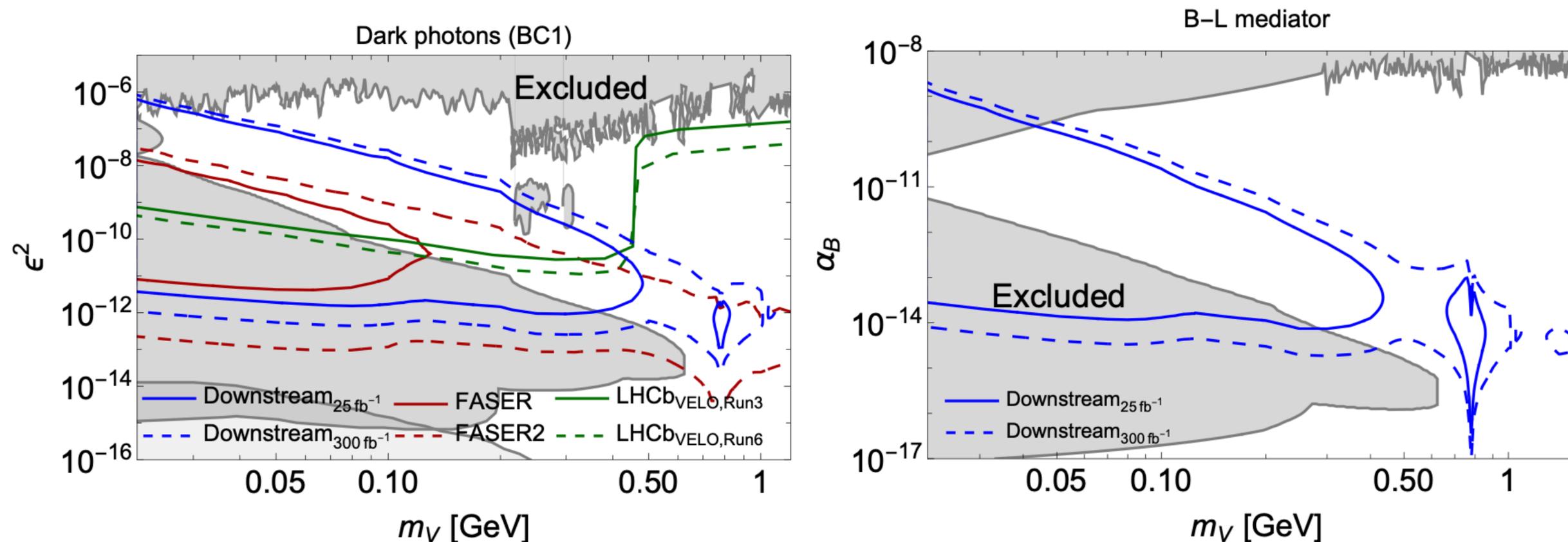
- These techniques are being adapted for BSM LLP searches
- Complementary detector acceptance to searches using Long and Downstream tracks
- Dedicated triggers will extend acceptance of LHCb's tracking system to around 8 m, lifetimes up to  $\mathcal{O}(10 \text{ ns})$  in regions of little-to-no physics background
- Example channel  $B^+ \rightarrow K^+ H' (\rightarrow \mu^+ \mu^-)$



# Downstream

## Dark photons and B-L mediators

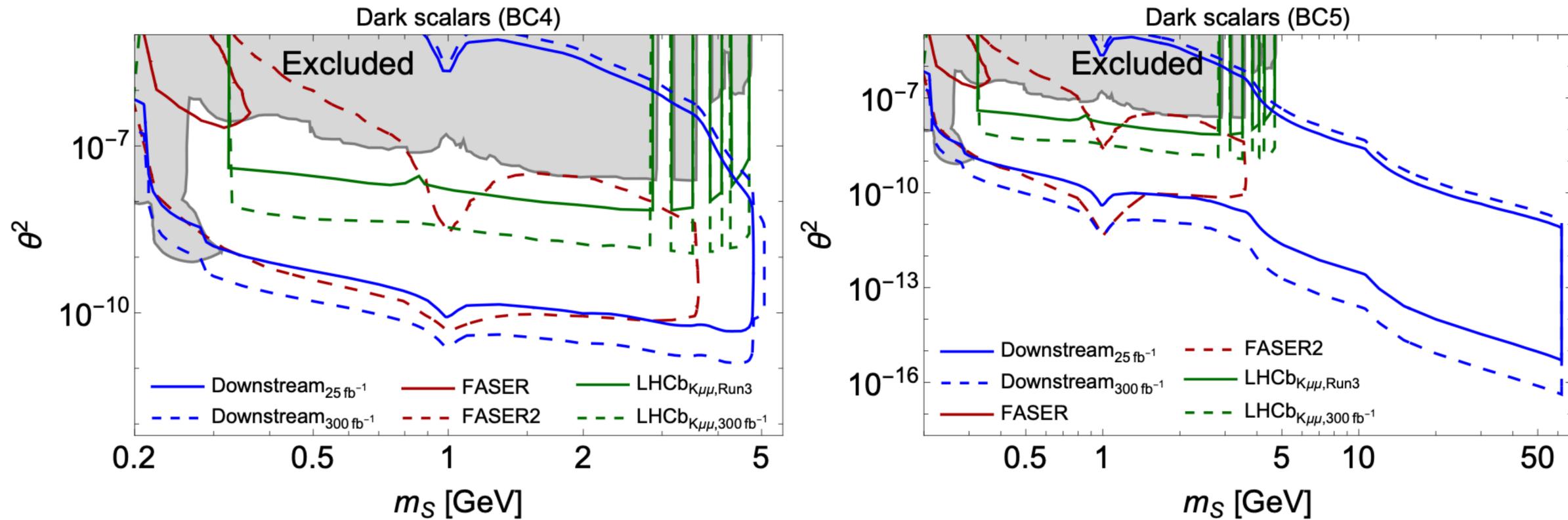
Model	Production	Decay modes
Massive photon [V] $U_{B-L}$ mediator	$\pi/\eta/\eta' \rightarrow VX$ Bremsstrahlung Drell-Yan	$\ell^+\ell^-$ , $\pi^+\pi^-$ , $\pi^+\pi^-\pi^0$ , $K^+K^-$



**Fig. 6.** Sensitivity to dark photons (*BC1*, the left panel) and  $B - L$  mediators (the right panel) in the plane LLP mass-LLP coupling. The sensitivity of future LHCb searches restricted by VELO is taken from [32], while the excluded parameter space and the sensitivity of FASER and FASER2 experiments is taken from [3]. For the *Downstream* algorithm, in this and subsequent figures, two values of the integrated luminosity are assumed:  $25 \text{ fb}^{-1}$ , corresponding to the partial statistics of Run 3, and  $300 \text{ fb}^{-1}$ , which is the full statistics of Run 6. For the description of the models, see Sec. 3 and Ref. [23]. See the text for the discussion on the sensitivity.

# Downstream Higgs-like scalars

Model	Production	Decay modes
Dark scalar [S]	$B_{(s)} \rightarrow SX_s$ $B \rightarrow SSX$ $h \rightarrow SS$	$\ell^+\ell^-$ , $\pi^+\pi^-$ , $K^+K^-$ , $c\bar{c}$ , $gg\dots$

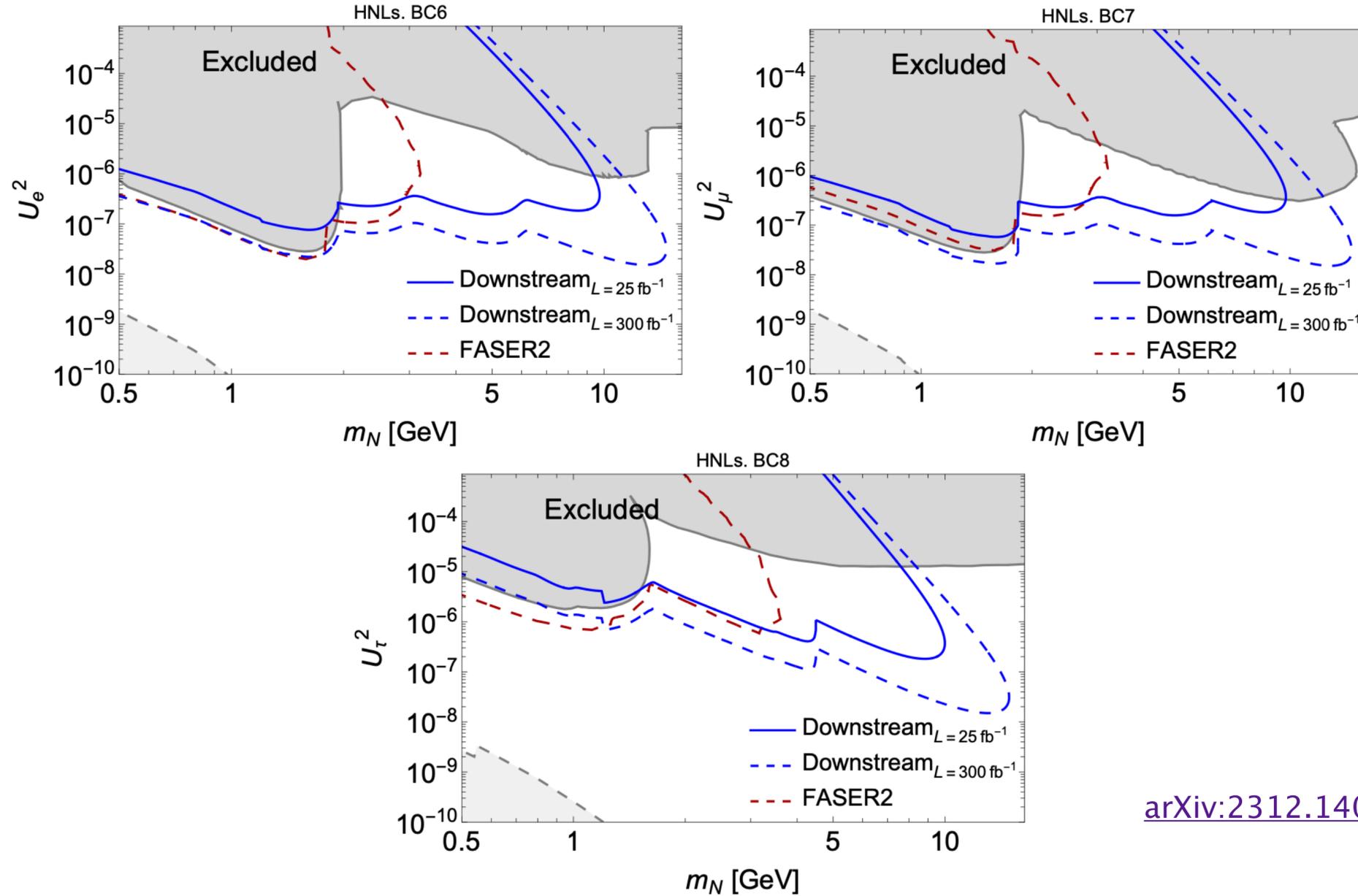


**Fig. 7.** Sensitivity to Higgs-like scalars, models  $BC_4$  (the left panel) and  $BC_5$  (the right panel). The excluded domain, as well as sensitivities of FASER, FASER2, and the search of  $B \rightarrow KS(\rightarrow \mu\mu)$  are taken from [3].

[arXiv:2312.14016](https://arxiv.org/abs/2312.14016)

# Downstream HNLs

Model	Production	Decay modes
Heavy lepton [N]	$B/D \rightarrow NX$ $W \rightarrow N + \ell$	$\ell q \bar{q}'$ , $\nu q \bar{q}$ $\nu \ell \bar{\ell}'$ , ...



[arXiv:2312.14016](https://arxiv.org/abs/2312.14016)

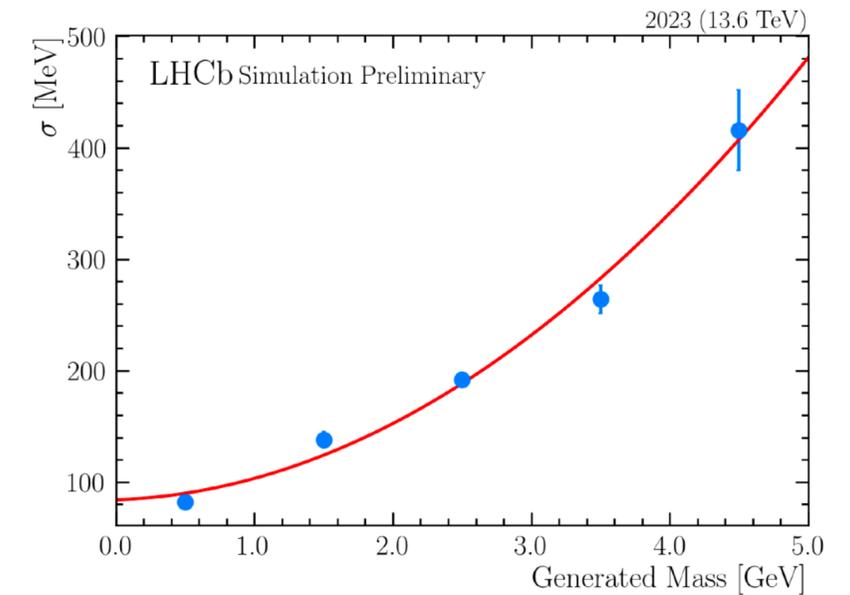
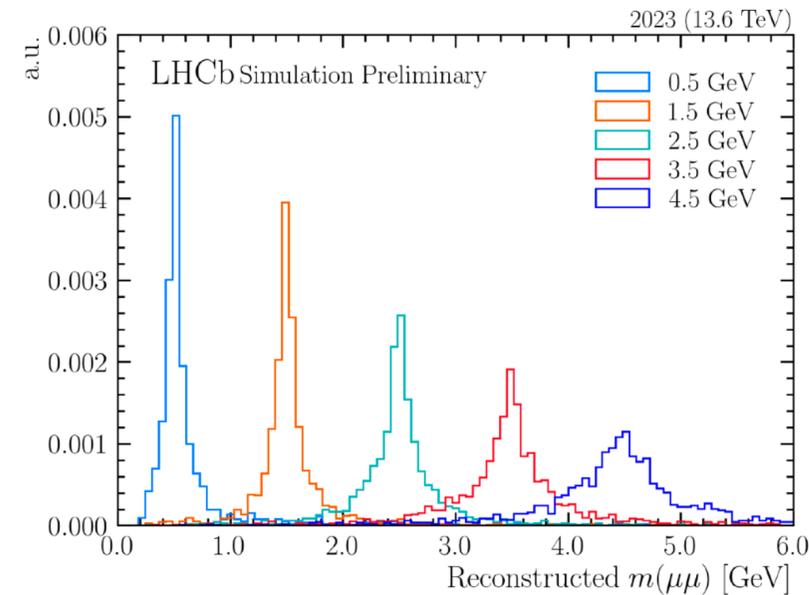
**Fig. 8.** Sensitivity to HNLs coupled solely to  $\nu_e$  (the top left panel),  $\nu_\mu$  (the top right panel), and  $\nu_\tau$  (the bottom panel). The parameter space excluded by past experiments as well as the sensitivity of FASER2 are taken from [3]. The bottom gray domain below the short-dashed line corresponds to the parameter space excluded by BBN [36; 37].

# T tracks

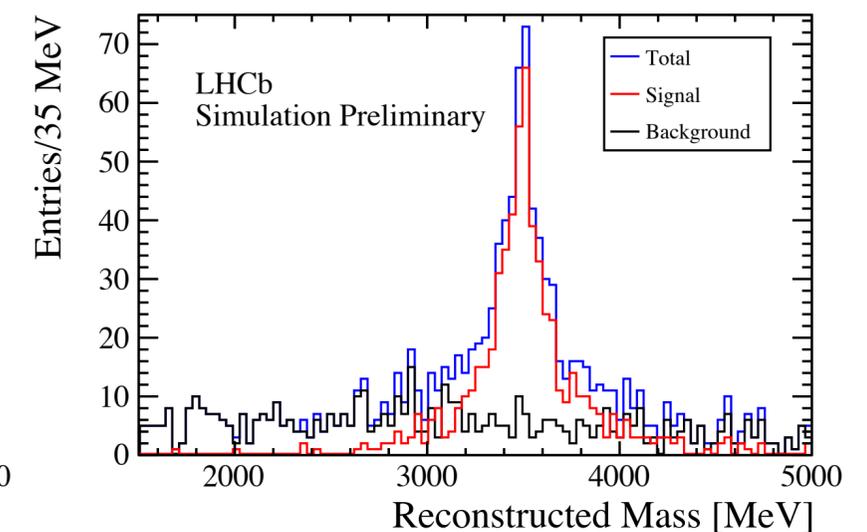
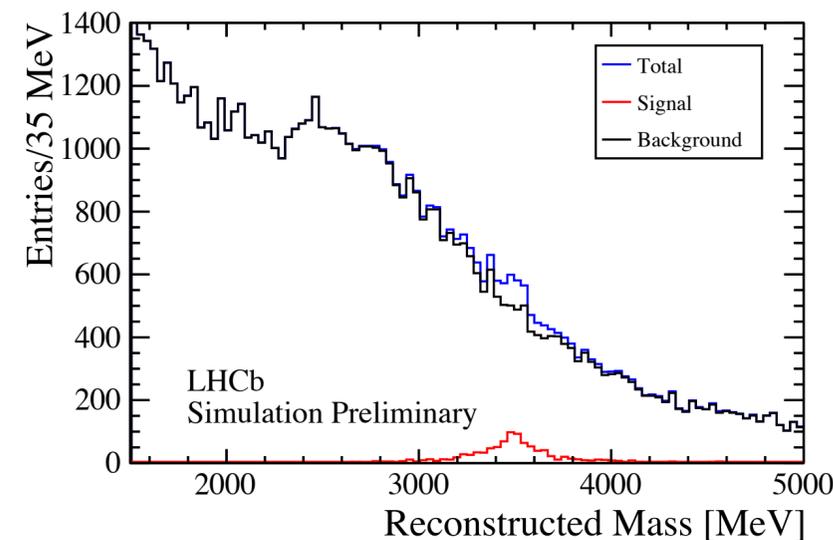
## Higgs-like scalars

- Trigger line development
- Dimuon invariant mass and mass resolution in trigger shown for 5 values  $m(\text{LLP}) < m(B) - m(K)$  for decays in magnet region
  - Could be improved offline using decay tree fit with  $B$  mass constraint
- Example of how combinatorial background can be suppressed through dedicated MVA-based track filtering

Variables:  $p_T, p_z, \text{IP}, \chi_{\text{IP}}^2, \Delta\text{LL}(p - \pi), \Delta\text{LL}(K - \pi), \Delta\text{LL}(\mu - \pi)^{\text{calo}}, t_x, t_y$



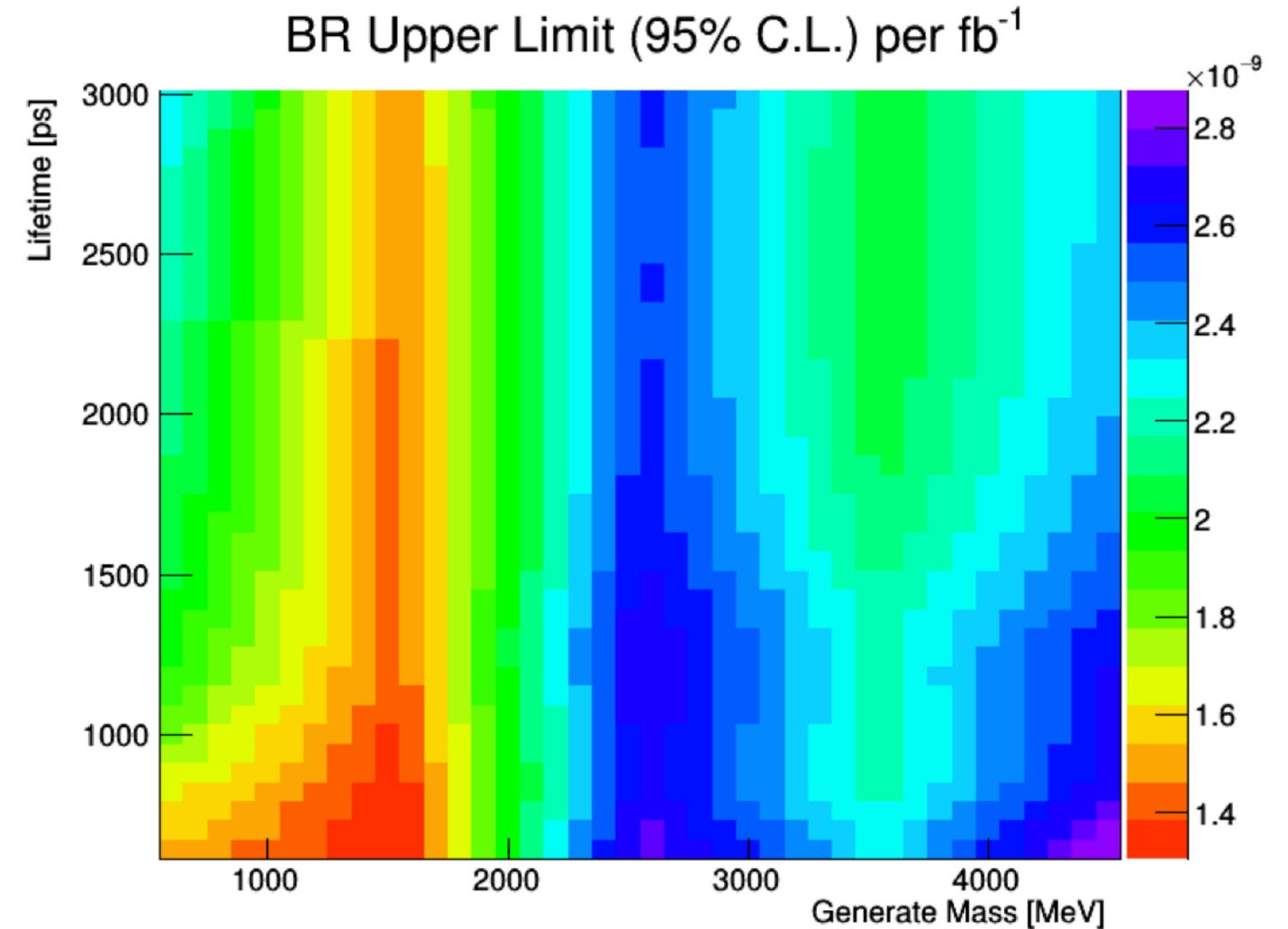
[LHCb-FIGURE-2023-026]



# T tracks

## Higgs-like scalars

- Estimated sensitivity based on selection
- Can improve current limits by 2 orders of magnitude for lifetimes over 0.1 ns



# Summary and conclusions

# Summary & conclusions

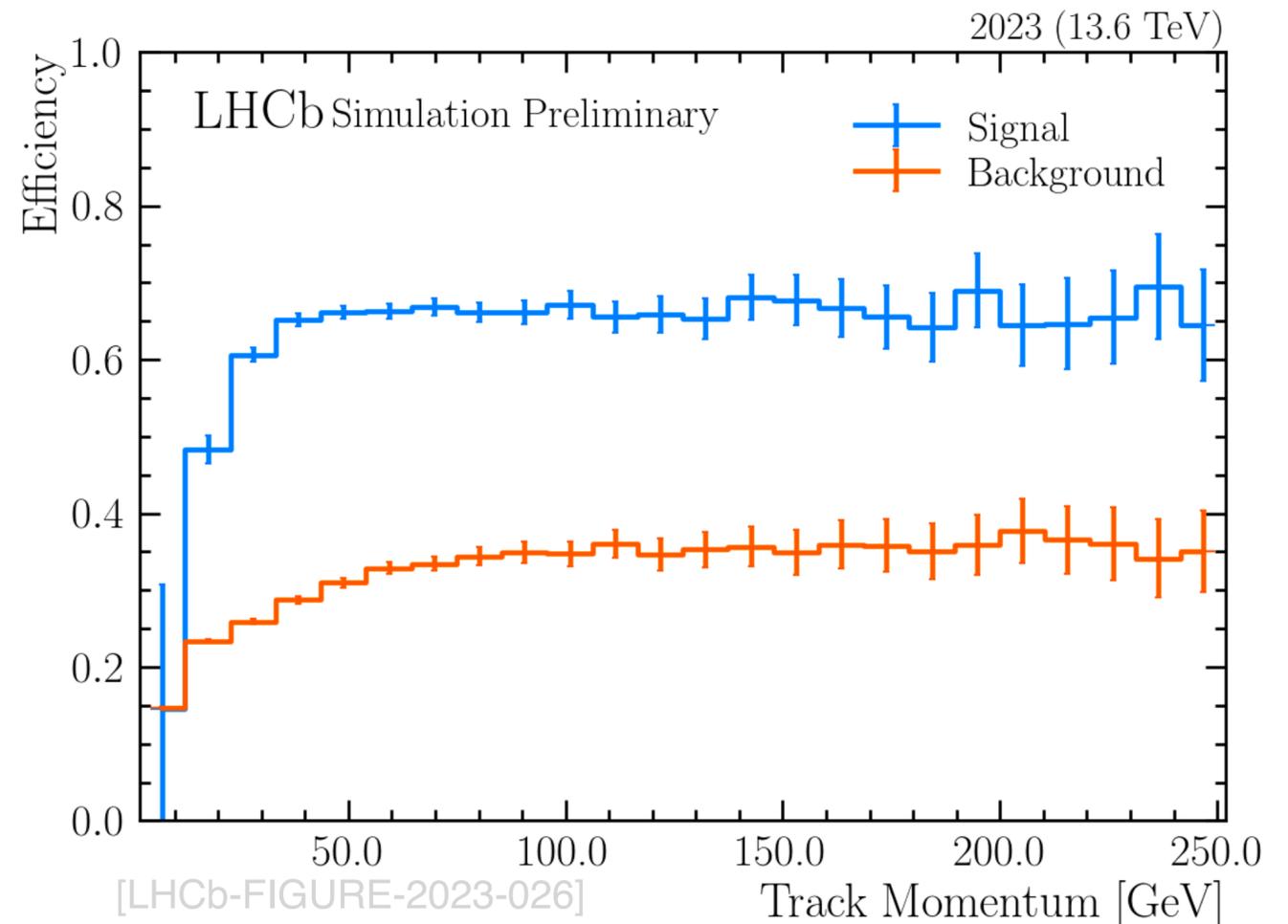
- The physics reach of LHCb is expanded by triggering on particles decaying more than 1 m from the interaction point
- Techniques have been developed for strange hadrons (SM LLPs) and are now being applied to BSM LLPs
- This extends the accessible lifetimes by several orders of magnitude
- This expand current limits by several orders of magnitude
- Next steps:
  - Finalise trigger lines for several different BSM signatures using Downstream and T tracks to collect some data to analyse

# Backup

# Topological track filtering

## HLT2

- Not all processes have clear signatures to reduce combinatorics
- Not possible to run reconstruction and extrapolate all T tracks in the event without significant throughput reduction
- Filter tracks before full reconstruction using two MVAs — gradient boosted BDTs from CatBoost library
- Use a BDT to **filter single tracks**, then use a BDT to **filter pairs (vertex candidates)** of remaining tracks
- Currently optimised for  $\Lambda$  and  $K_S^0$
- **Reduces impact on throughput** and combinations by 70%-85% whilst maintaining around 70% of signal



- BDT variables are:

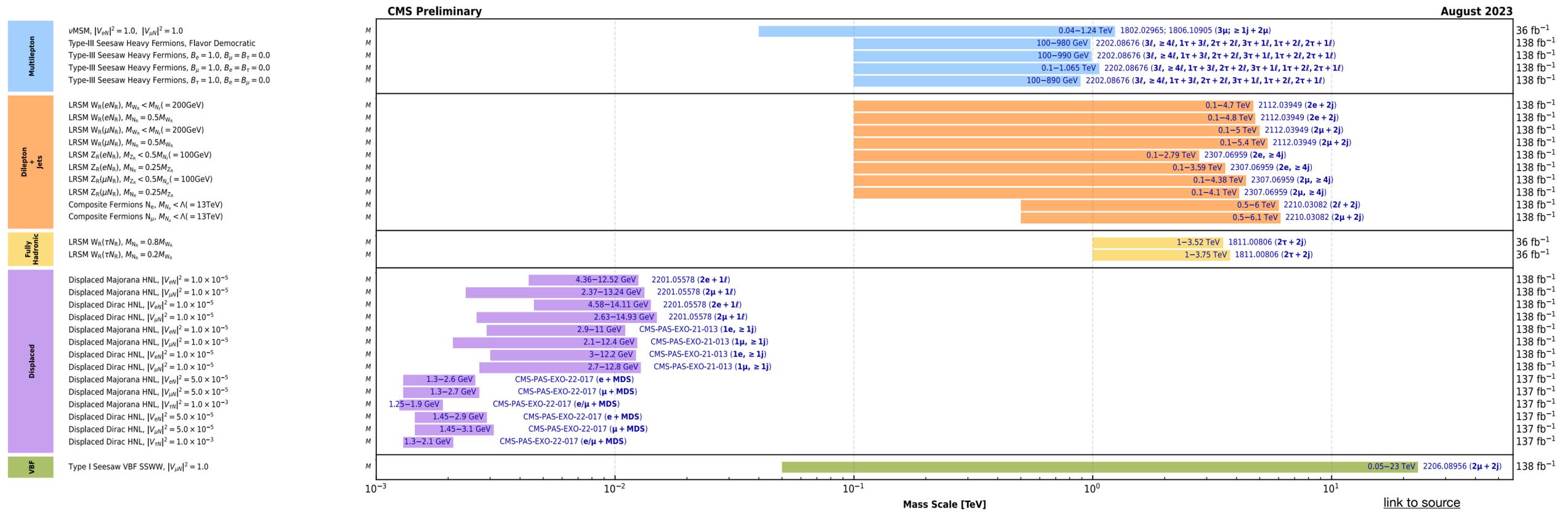
Single track:  $p_T, p_z, \eta, y, r$

Track pair:  $\Delta y, \Delta r, \text{sign}(t_y^1 \cdot t_y^2), \Delta t_y, \Delta t_x, y_{yz}, z_{yz}$

- Currently deployed in trigger for  $\Xi_c^0 \rightarrow \Lambda K^- \pi^+$ ,  $\Xi_c^0 \rightarrow \Xi^- \pi^+$ ,  $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$  decays
- Performance expected to improve in 2024 as closed VELO and UT will improve Long and Downstream tracking → less background

# CMS HNL

## Overview of CMS HNL results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

# Previous measurements in LHCb

## (Incomplete)

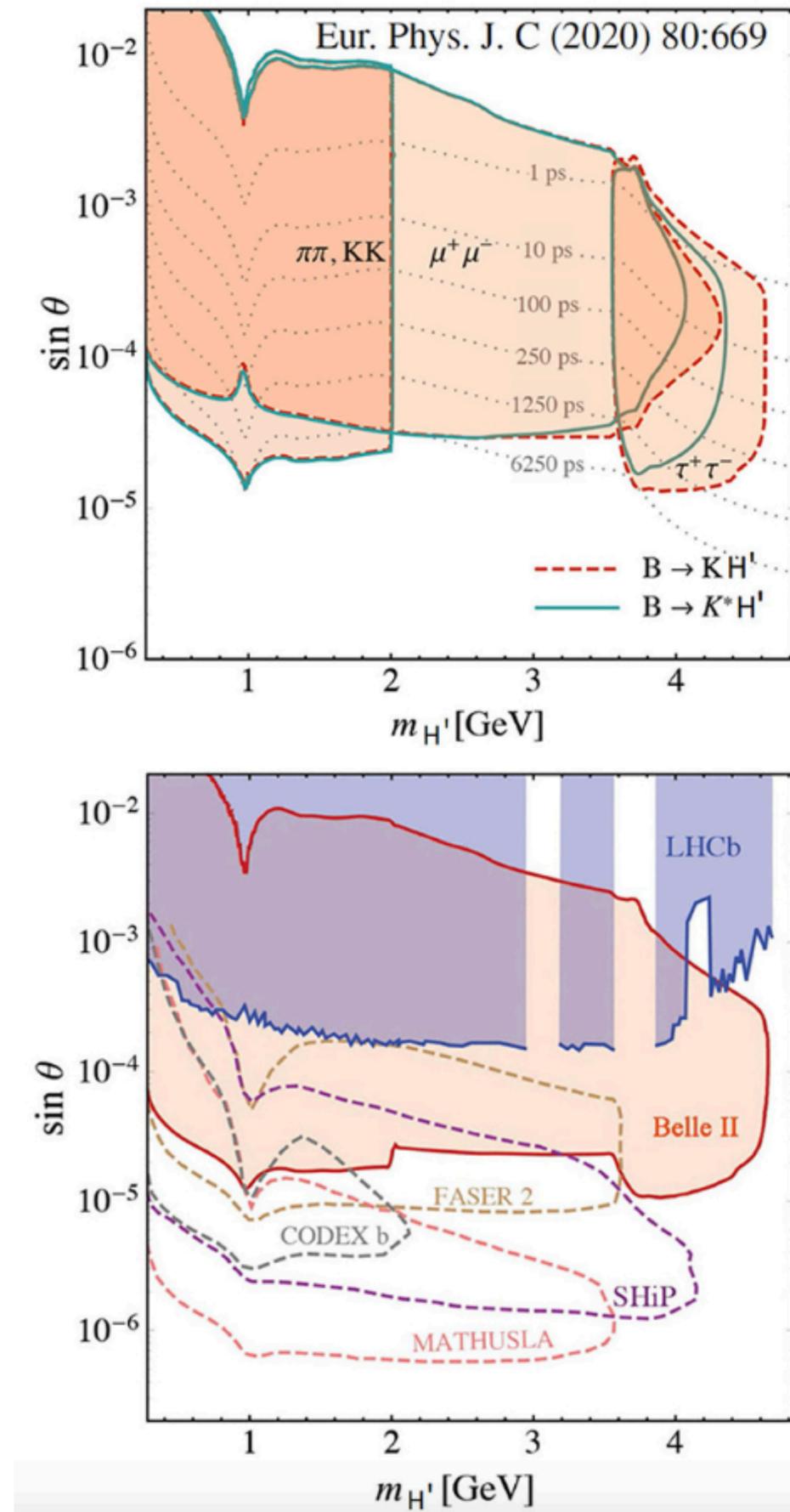
- 7 TeV:
  - EUR. PHYS. J. C75 (2015) 152, “Search for long-lived particles decaying to jet pairs” | A search is presented for long-lived particles with a mass between 25 and 50 GeV/c<sup>2</sup> and a lifetime between 1 and 200 ps ([link](#))
  - EUR. PHYS. J. C76 (2016) 664, “Search for Higgs-like bosons decaying into long-lived exotic particles” | A search is presented for massive long-lived particles, in the 20-60 GeV mass range with lifetimes between 5 and 100 ps. ([link](#))
- 7 and 8 TeV:
  - EUR. PHYS. J. C77 (2017) 224, “Search for massive long-lived particles decaying semileptonically in the LHCb detector” | The mass range from 20 to 80 GeV and lifetimes from 5 to 100 ps are explored. ([link](#))
  - PHYS. REV. D95 (2017) 071101, “Search for long-lived scalar particles in  $B^+ \rightarrow K^+ \chi(\mu^+ \mu^-)$  decays” | No significant excess is observed in the accessible ranges of mass  $250 < m(\chi) < 4700 \text{ MeV}/c^2$  and lifetime  $0.1 < \tau(\chi) < 1000 \text{ ps}$ . ([link](#))
  - EUR. PHYS. J. C77 (2017) 812, “Updated search for long-lived particles decaying to jet pairs” | A search is presented for long-lived particles with a mass between 25 and 50 GeV/c<sup>2</sup> and a lifetime between 2 and 500 ps
  - EUR. PHYS. J. C81, (2021) 248, “Search for heavy neutral leptons in  $W^+ \rightarrow \mu^+ \mu^\pm + \text{jet decays}$ ” |
- 13 TeV
  - PHYS. REV. LETT. 124 (2020) 041801, “Search for  $A' \rightarrow \mu^+ \mu^-$  decays” | The prompt-like  $A'$  search explores the mass region from near the dimuon threshold up to 70 GeV, and places the most stringent constraints to date on dark photons with  $214 < m(A') \leq 740 \text{ MeV}$  and  $10.6 < m(A') \leq 30 \text{ GeV}$ . The search for long-lived  $A' \rightarrow \mu^+ \mu^-$  decays places world-leading constraints on low-mass dark photons with lifetimes  $\mathcal{O}(1)$  ps.
  - EUR. PHYS. J. C82 (2022) 373, “Search for massive long-lived particles decaying semileptonically at  $\sqrt{s}=13 \text{ TeV}$  | The analysis covers LLP mass values from 10 GeV up to about one half the Higgs-like boson mass. The second LLP production mode is directly from quark interactions, with LLP masses from 10 to 90 GeV. The LLP lifetimes considered range from 5 to 200 ps.

Experiment	$\mathcal{L}(\text{fb}^{-1})$	$(z_{\min}, z_{\max})(\text{m})$	$(\theta_{\min}, \theta_{\max})(\text{mrad})$	Selection
LHCb with <b>Downstream</b>	25 (w FASER) 300 (w FASER2)	(1,1.5)	$\approx (1.3, 260)$	Two oppositely charged particles enter SciFi, $p > 5 \text{ GeV}/c$ $\epsilon_{\text{rec}} \approx 0.4$
FASER	150	(480, 481.5)	$\approx (0, 0.21)$	Two particles with zero total charge intersect the detector
FASER2	3000	(480, 485)	$\approx (0, 2.1)$	Two particles with zero total charge intersect the detector

**Table 2.** Setups of the LHCb with the **Downstream** algorithm and the FASER and FASER2 experiments used for the comparison of the signal rates. The columns are: the name of the experiment, the integrated luminosity, the minimal and maximal longitudinal displacement covered by the decay volume, the minimal and maximal angles covered by the decay volume, and the selection criteria imposed on the LLP decay. Two different luminosities are considered for the **Downstream** algorithm in order to make a proper comparison with FASER/FASER2 (see text for details).

# Higgs portal

- Some models predict the SM Higgs field serving as a portal to a dark sector
- One of simplest models predicts a mixed state between a new scalar low mass Higgs ( $H'$ ) and the SM Higgs ( $H$ ), determined by the mixing strength  $\theta$ 
  - $h = H \cos \theta - H' \sin \theta$
- In this model  $H'$  can be interpreted as a mediator with unknown mass and lifetime to a dark sector
- Measured through the decay  $B \rightarrow KH'(\rightarrow xx)$  with  $x = e, \mu, \tau, \pi, K, D, g$  etc



**Figure 8.** Parameter space regions for the  $B \rightarrow H'K$  and  $B \rightarrow H'K^*$  decay channels (top) and sensitivity to the  $H'$  displaced vertex by different present and future experiments (bottom), (Figures adapted from [Kachanovich, Aliaksei et al., 2020](#)).

# Heavy Neutral Leptons

- Heavy Neutral Lepton  $N$  coupled to the active neutrino  $\nu_\alpha$ :  $\nu_e, \nu_\mu, \nu_\tau$
- Below EW scale, coupling of HNLs to SM neutrinos is via mass mixing with the active neutrinos parametrised by HNL-neutrino mixing  $U_\alpha$